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A HISTORICAL PERSPECTIVE OF AIRCREW SYSTEMS EFFECTS ON AIRCRAFT DESIGN

by

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A HISTORICAL PERSPECTIVE OF AIRCREW SYSTEMS EFFECTS ON AIRCRAFT DESIGN

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ABSTRACT

The design of the aircrew workstation often has not been an orderly part of the overall aircraft design process but rather of much lower priority than the integration of the airframe and powerplant. However, the true test of the aircraft is how well the aircrew can use the aircraft for mission performance. NAVAIR has been seeking the establishment of an Aircrew Centered System Design discipline, to be addressed as an integral part of the global aircraft system design process. A baseline, historical understanding of how the aircrew have been integrated into the aircraft and mission is needed. An analysis was conducted of several significant airplanes from the Wright Flyer to the present, seeking those design factors which affected how well the aircrew were able to perform the design mission. The physical and attentional resources of the aircrew must be understood and accommodated by those designing the cockpit and other workstations. Aircrew members who are knowledgeable of, and experienced in the intended mission must be involved in the design process from the very earliest phases of concept definition.

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I. INTRODUCTION

A. GENERAL

The evolution of cockpit design from the days of the Wright brothers to the present has not necessarily been smooth and well ordered or even recognized as being valuable. Cockpit design has often not been part of the overall design process. The design of the cockpit, the integration of controls and displays has frequently been of much lower priority than the integration of airframe and powerplant. The airplane however must be operated by the aircrew. The mission success of that airplane can in large measure depend upon how well the aircrew have been designed into the airplane.

The increasing capabilities of the aircraft and systems to include communications, navigation , weapons, and mission management systems have led to increasingly complex cockpits. The most common approach to designing the aircrew system has been to add controls and displays while assuming the aircrew just adapt. Figure 1 shows the trend for display complexity in the cockpit.

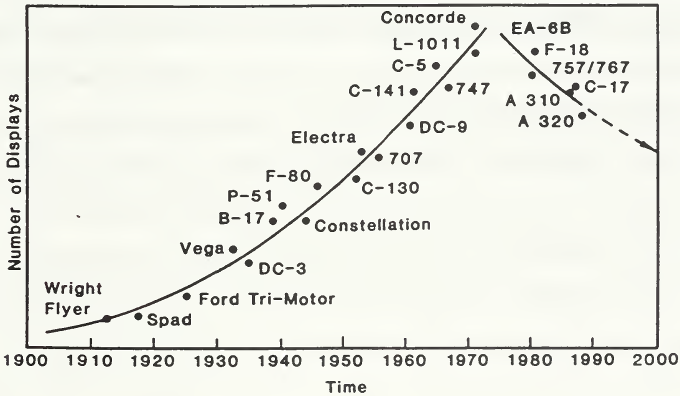


Figure 1. Growth in Number of Displays. From Ref. [1].

The maxima in the curve after the Concorde is significant. At this time, several airplanes were being developed with considerable human factors involvement in the design effort. Most notable were the F-15, F-16 and F/A-18. These aircraft capitalized upon the use of multipurpose displays with sensor integration and automation of display modes.

The overall approach of this thesis is to evaluate from a design practice reference, the cockpits of selected aircraft from the Wright Flyer to recent times. An understanding of how aircrew have been integrated into the aircraft and mission is one purpose of this thesis. The other purpose is to assess how well the aircrew were able to perform the intended missions and which design decisions affected mission performance. This thesis will describe the necessity to recognize that the aircrew requirements are an integral part of the overall system design.

B. ONE AIRCRAFT DESIGNER'S VIEW OF HUMAN FACTORS

J. H. 'Dutch' Kindelberger was one of the most famous designers of WW II and post war aircraft at North American Aviation His designs included the P-51 Mustang, B-25 Mitchell, F-86 Sabre and F-100 Super Sabre. Kindelberger went on to become the board chairman of North American Aviation. His views on the role of the pilot, and man-machine interface were not at all uncommon in the 1950s and can even be seen in the current debate over unmanned air vehicles (UAVs), cruise missiles, drones and manned aircraft. In reviewing the human factors involved in the F-86 Sabre design, Kindelberger discussed the hostility to basic human survival of conditions in the stratosphere, the complexity of the fighter mission and the accommodations which the aircraft designers must make for human pilots. "[The pilot] must be enclosed in a heated and pressurized compartment, and he must have pure oxygen pushed into his lungs under pressure." Due to the low density of the atmosphere and its deleterious effect on the thrust, lift and control of the Sabre "the pilot must make every maneuver with delicate precision." [Ref. 2]

Kindelberger then goes on to enumerate the many systems packed into a jet fighter, with which the pilot must interact: engine, cockpit controls and displays, electrical and hydraulic systems, communication and fire-control systems. "And there he sits, loaded down with protective clothing, parachute, G-suit, crash helmet, oxygen mask, and an acute bellyache caused by expansion of his body gas at high altitude." [Ref. 2]

Kindelberger continues his assessment of the pilot's meager capabilities which lead to inadequacy in combat.

> Now the reason he is eight miles above the Korean landscape is to find another airplane and if possible to shoot it down. Here his senses prove pretty inadequate, for the reasons that both his airplane and the enemy airplane are moving fast, and that his spatial perception is impaired by such things as a lack of reference points...Not only are his senses inadequate to see the other plane and judge its relative position and speed, but his reaction time is often too slow for proper control of his airplane and his guns. [Ref. 2]

Next, Kindelberger discusses the limitations a pilot imposes on the airplane: "From this brief description of some phases of a present-day fighter mission we see that our flying machines are rapidly approaching capabilities that are penalized rather than aided by the presence of a human pilot." [Ref. 2] He then enumerates the accommodations which an aircraft designer must make

> We have to give the man something to breathe and create an artificial atmospheric pressure for him. We have to cool and warm his body as the ambient temperature varies. We have to provide for his physical volume and weight and comfort, and we have to put in scores of devices to insure his survival in an emergency.
>
> Finally, because his senses are not sufficiently acute and his reaction time is not fast enough to enable him to guide the machine in all the split-second phases of its military mission, we must install devices that not only control the machine automatically, but also waste extra weight and space informing the human pilot what the machine has been told. [Ref. 2]

Kindelberger thus not only views with regret the requirement to provide weight and volume for the pilot, but must also more volume, weight and systems to keep him not only alive, but comfortable. Further, once these accommodations are made, the human pilot is

then in his view not even adequate to the task at hand of finding, engaging and destroying the enemy as efficiently as automatic systems could.

While Kindelberger made these remarks, an engineer within his own company was leading a design effort to build a hypersonic research airplane. This airplane design was strongly influenced by pilot input and pilot decisions. As will be demonstrated in the case studies to follow, the effectiveness of any aircraft/pilot combination to achieve mission success is dependent on how well the human operators' strengths and weaknesses are accommodated. The success of this particular airplane in accomplishing the design mission, and going beyond the program's initial goals was dependent upon having a pilot aboard. The success and constancy of the pilots' performance was even cited as a benchmark to which some of the automatic systems installed could only hope to attain.

II. WRIGHT FLYER

A. SUCCESS DUE TO SYSTEMS ENGINEERING METHODOLOGY

Wilbur and Orville Wright constructed the first successful airplane which flew on 17 December 1903 at Kill Devil Hill, North Carolina, as illustrated in Figure 2. They were not tinkerers who stumbled onto the magic formula of flight. They were in fact thorough engineers, dedicated researchers and test pilots. As noted by John Anderson [Ref. 3] the Wright brothers were "the first to treat a flying machine as an *integrated system* involving aerodynamics, propulsion, structures, and flight dynamics. They fully appreciated the interaction and mutual importance of all these aspects. In this sense, they were the first to build a *total* flying machine - a machine which had all the major aspects that a modern airplane has today." The Wright brothers also recognized the role of the pilot as a vital part

Figure 2. Wright Flyer, December 17, 1903. From Ref. [3].

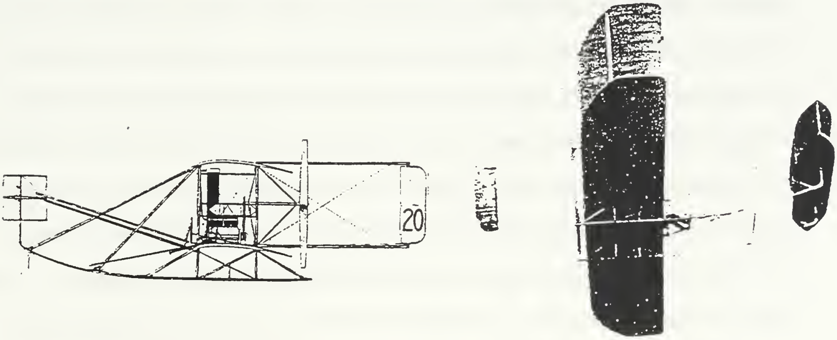
of that integrated system. They designed their Flyers with an aircrew centered methodology which focused on the pilot controlling the airplane. The aviator provided the active control of the flight path vector of the machine and was not merely talking ballast. They typified what aviation historian Charles Gibbs-Smith termed the "airman" philosophy [Ref. 3]. This is contrasted with the "chauffeur" philosophy of Sir George Cayley, Sir Hiram Maxim, and their most direct competitor, Samuel P. Langley. It is instructive to examine the early airplanes of the Wright brothers for the aircrew centered system design aspects incorporated therein.

B. WRIGHT FLYER MODELS ANALYZED

The Wright brothers developed four airplanes between 1903 and 1907 which are relevant to the current discussion. The aircraft to be analyzed are four of the five canard configured ("horizontal rudder" in the Wright brothers nomenclature) Flyers. These include the 1903, 1904, 1905, and 1907 Flyers. The Flyers are shown in Figures 2,3,4, and 5, respectively. The fifth canard configured airplane was the 1909 model which was built to meet U. S. Army Signal Corps specifications. It was a considerably different machine with over 50% more wing area among other differences and will not be discussed further.

Figure 3. 1904 Wright Flyer. From Ref. [3]

Figure 4. 1905 Wright Flyer. From Ref. [3]



a. Side Elevation

b. Orville aboard.

Figure 5. 1907 Wright Flyer. From Ref. [Ref. 3]

According to Frederick Hooven [Ref. 3] the four airplanes can be "divided into two types aerodynamically: the 1903 and 1904 machines which differed only in small respects, and the 1905 and 1907 models which were substantially identical to each other." The two types differed mainly in the size and deflection range of the horizontal stabilizer, while the wings were aerodynamically identical and of equal area. The 1903 Flyer only flew four times on 17 December 1903 and was destroyed the same day when blown over by a wind gust. The 1904 Flyer had a more powerful engine, rated by the Wright brothers at 16 horsepower, vice the 12 horsepower of the earlier airplane. The 1905 Flyer had a more powerful engine than the 1904 version and was wrecked on its eighth flight in an apparent oscillatory pitch divergence. This is not surprising given that F.E.C. Culick and Henry R. Jex [Ref. 3] found that the aircraft had a lightly damped phugoid motion with a period of six seconds, no short period and a propensity to pilot-induced oscillation (PIO). During just such a PIO, the 1905 Flyer impacted the ground destroying much of the structure and ejecting Orville through the upper wing. He was fortunately unhurt. The 1905 Flyer also featured a independent control of wing warp and rudder deflection through a control stick mechanism for roll and yaw control. This replaced the mechanically interconnected wing warp and rudder control mechanism activated by a hip cradle, which was used for lateral and directional control system on their gliders and early Flyers. Hooven terms the 1905 Flyer the first real airplane. It was the first airplane to have a high duration maneuvering flight of 39 minutes, before any other powered airplane became airborne. The 1907 Flyer was aerodynamically similar to the 1905 model, but was heavier. The 1907 machine was upgraded to a 30 horsepower engine and upright seating for pilot and a passenger. At least seven of the 1907 Flyers were built, one of which still is on exhibit in the Deutsches Museum in Munich, Germany. The 1907 Flyer was the model demonstrated by Orville to the Signal Corps, in Washington D.C. It was during this demonstration series that another crash occurred, resulting in the death of Lieutenant Selfridge. In 1908, the 1905 Flyer was rebuilt with a 30 horsepower engine and upright seating for two. The 1908 rebuilt version

of the 1905 Flyer, (hereinafter termed 1908/1905 Flyer) was demonstrated by Wilbur in Paris. This airplane still exists, having undergone a restoration which began in 1948, before the death of Orville. The 1908/1905 Flyer was considered a success by the Wright brothers and thus they undertook commercial sales of Wright Flyers. [Ref. 3]

C. STABILITY AND CONTROL OF THE WRIGHT FLYERS

1. General

The Wright brothers were first and foremost pilots. They embraced wholeheartedly the airman philosophy. On land, they were bicyclists, both as racers and as manufacturers. The bicycle is unstable and must be actively controlled by the rider. Thus, the Wrights were not then deterred by an unstable airplane design. The Wrights viewed the airplane as an aircrew centered system, requiring an active operator, a pilot who supplied control and maintained equilibrium. They recognized that they must not only develop a powered airplane but they had to develop a control system and the piloting skills to operate the airplane. [Ref. 3]

2. Longitudinal Stability and Flying Qualities

The locations of the aerodynamic center (a.c.), moment center and center of gravity (CG) of the 1903 Flyer are illustrated in Figure 6. The 1903 Flyer had the aircraft neutral point at 10% chord aft of the wing leading edge and the aircraft center of gravity at 30% chord aft of the wing leading edge. The static margin was thus -20%. A statically stable airplane requires a positive static margin in order to have restoring moments following a disturbance in pitch. Current practice calls for the static margin of a non-augmented aircraft to be not less than +10%. An aircraft with an automatic flight control system (AFCS) can have a static margin of approximately -5%. The Wright Flyer was unstable and barely controllable: the locations of the a.c. and CG illustrate how demanding the airplane actually was to fly. [Ref. 3]

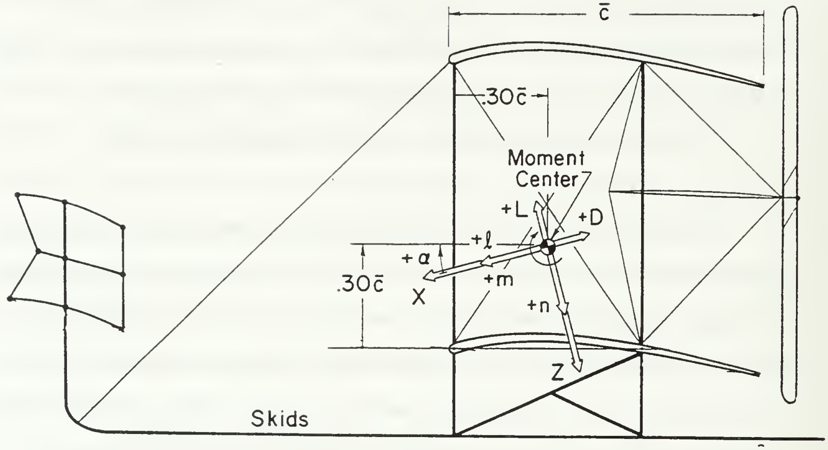


Figure 6. 1903 Wright Flyer [after Ref. 3].

The Wrights were aware of positive static stability, the impact of center of gravity location on stability and tail aft configurations. The 1900 glider was of the same type canard configuration and normally flown as such stabilizer first. In experimenting with static stability and positive static margin, they had flown the 1900 glider backwards to achieve a statically stable, tail aft airplane. Figure 7 presents some combinations of configurations and stability options. [Ref. 3]

The "conventional" aircraft arrangement with aft horizontal stabilizer and positive static stability is illustrated in Figure 7.1. When the wing is stalled, the airplane will have pitch control through the unstalled horizontal tail. It will however, have a tendency to pitch nose down after the stall. Given enough altitude, this allows recovery from the stalled condition. The stable canard of Figure 7.2 will pitch nose down if the forward surface stalls first, but precise pitch control is not possible.

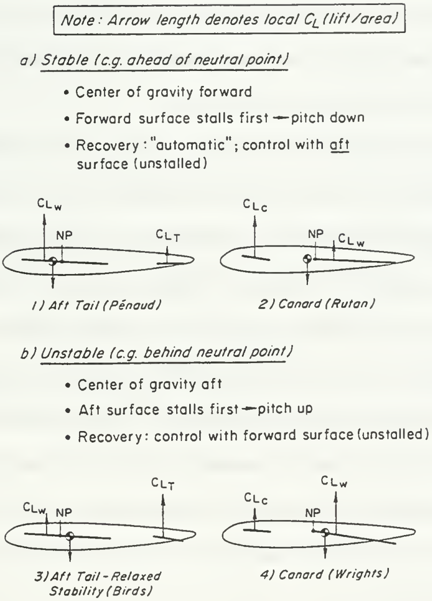


Figure 7. Wing and tail configurations. [From Ref. 3].

The relaxed static stability, aft tailed aircraft of Figure 7.3 would be very difficult to fly, with a very short time to double amplitude in pitch. The unstable canard configuration selected by the Wright brothers is illustrated in Figure 7.4. With proper rigging, even if the main wing were to stall, the horizontal stabilizer would still have authority to control pitch attitude.

The Wright brothers were frequent correspondents with Otto Lilienthal, an early gliding pioneer in Germany. They were deeply affected by Lilienthal's death in 1896 while flying a statically stable tail aft, glider. Lilienthal's glider stalled, the nose pitched down resulting in a dive and impacted the ground. The Wright brothers realized from gliding

experiments that such a stall was likely and that their flight training would be at low altitudes with little margin for a nose down pitch motion. Thus they made an aircrew centered system design decision to provide the pilot with positive pitch control authority through the entire flight regime including post stall. The pilot was essential to provide the control of the unstable aircraft which resulted.

The Wright brothers were the first experimenters to use the canard configuration. Their analysis leading to the selection of this arrangement was driven by the pilot's handling qualities requirements in the low altitude, low airspeed self taught flight training arena. It proved to be successful in avoiding stalled, nosedown pitching ground impacts. During gliding tests in 1901, Wilbur recovered from stalled conditions at least twice through the pitch control afforded by the canard. He was able to lower the nose and the glider mushed to the ground without serious damage. This convinced them of the correctness of their design choice. The canard provided instructional feedback by allowing them to see the results of control inputs on the control surface directly in front of them. The canard also provided a visual attitude reference, and thus was the only "instrument" on the early Flyers. [Ref. 3]

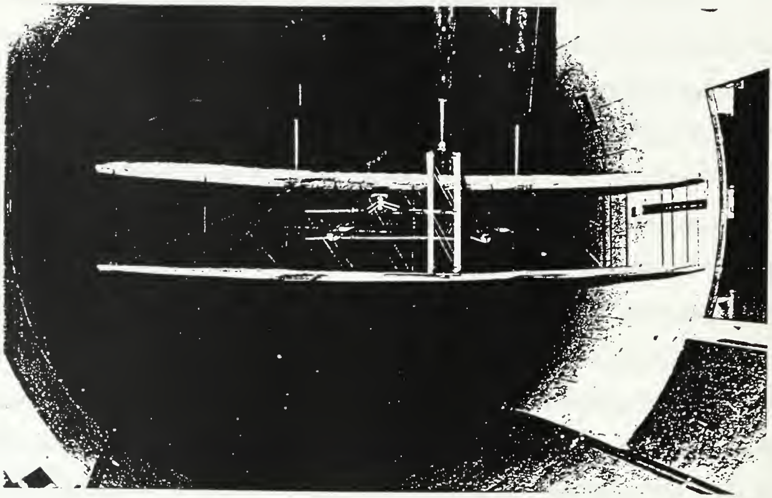
The canard design choice was based upon pitch control authority and not stability. The Wrights and their contemporaries did not recognize the current concept of stability. Stability analysis at the time did not include the notion of balancing moments. Thus a stable airplane was not predictable or sought. The main effort for them was controllability. Design changes to improve control authority could affect stability, sometimes unfavorably. [Ref. 3]

While many of the pioneering aviators, including Lilienthal, used weight shift for control, the Wright brothers pursued the design of control surfaces to provide control. As Hooven wrote " They wanted to have the machine go where they directed it to go, not where it chose to go or where the wind might take it. They were riders of bicycles and were not afraid of instability." [Ref. 3].

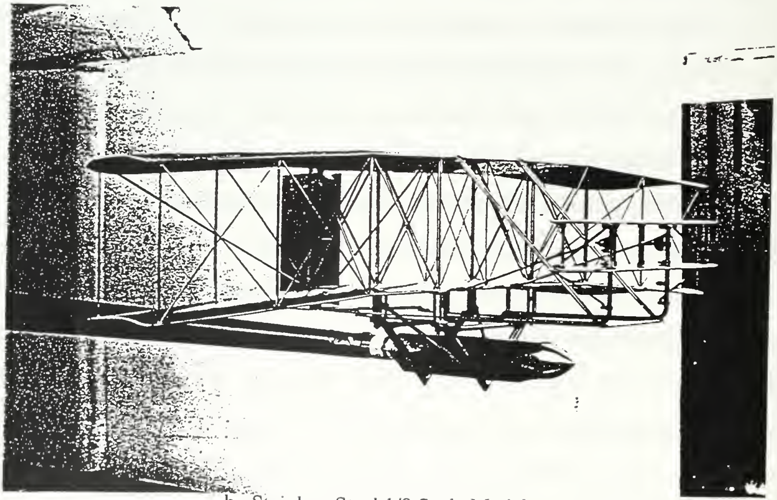
In pursuing controllability at the expense of the current concept of stability, they were perhaps too successful. The flight path of the Wright Flyers, was marked by what they termed "undulations". Culick and Jex [Ref. 3] state that the "unstable pitching characteristic of the 1903 Flyer is arguably its worst feature." This was revealed by a vortex lattice analysis, and wind tunnel analysis performed at the California Institute of Technology using both the stainless steel 1/8th scale model and the fabric covered 1/6th scale model shown in Figure 8; the test results are presented in Figure 9.

As seen in Figure 9, the analyses show that the Flyer had an unstable pitching moment. The Wright brothers were able to fly successfully only because of the synergy of three factors: the low speed (approximately 44 feet per second), the high pitch damping of the aircraft and not the least, their skill as pilots. The Culick and Jex analysis indicates that the 1903 Flyer had a lightly damped phugoid oscillation with a period of approximately six seconds and essentially no short period. Current general aviation airplanes have a phugoid period of 30 - 40 seconds and a short period of approximately 1 second. [Ref. 3]

The Wright brothers recognized the difficulty in controlling the pitch of the 1903 Flyer. Thus the subsequent Flyers incorporated aircrew centered design changes including the addition of ballast, changes in control system actuation, control surface size in an effort to improve flying qualities. The 1904 Flyer (Figure 3) was initially the same as the 1903 Flyer. The Wrights attempted to correct the pitch instability, the "undulations" with ballast. Initially, their analysis was that more elevator control power was needed to stop the pitch divergence. Ballast was added to the aft section of the 1904 Flyer. This caused the CG location to move further aft to 32% chord. The static margin was made even more negative at -22%. This was of course in the wrong direction for stability and exacerbated the undulations. The aft ballast was removed and 70 pounds of ballast were added to the stabilizer structure moving the CG location forward to 23% chord. This reduced the



a. Fabric Covered 1/6 scale Model



b. Stainless Steel 1/8 Scale Model

Figure 8. Models of 1903 Wright Flyer in California Institute of Technology Wind Tunnel. From Ref. [3].

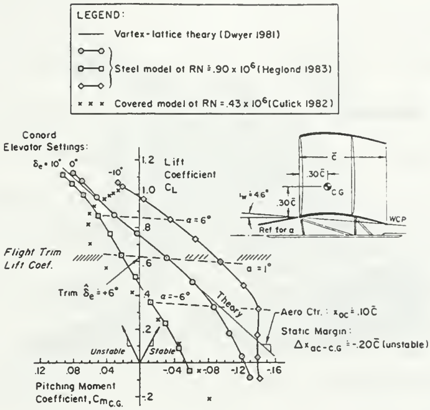


Figure 9. Comparison of Pitching Moment Analysis and Tests of 1903 Wright Flyer. From Ref. [3].

negative static margin to 13%, elevator responsiveness (control power) was reduced, and increased the phugoid period. These aircrew centered design changes made the aircraft more manageable in pitch for the fledgling aviators. [Ref. 3]

The 1905 Flyer was wrecked on its eighth flight on 14 July 1905. On 24 August 1905 it flew again with a larger canard. The Wrights understood that the pilots were having difficulty with "undulations" and accepted the aircrew centered design changes to cure this characteristic. [Ref. 3]

The Wrights themselves noted the power of CG location when comparing the flying qualities of the 1908/1905 Flyer with the 1907 Flyer. Both aircraft had upright seating for two. The 1908/1905 Flyer is shown in Figure 10. Wilbur and passenger (whose skirt is securely bound by twine in an effort to preserve modesty) are seated with knees just at the wing leading edge. In Figure 5b, Orville is seen seated with his legs fully extended

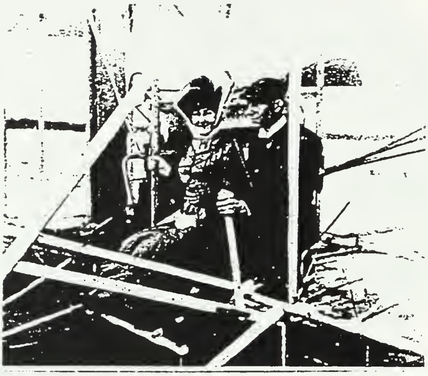


Figure 10. 1908/1905 Wright Flyer with Upright Seating and Passenger. From Ref. [3].

forward of the wing leading edge and his backside just on the leading edge. This yielded a more forward CG location. The difference was such that the 1907 Flyer had a CG location at 20% of chord, while the 1908/1905 Flyer had a CG location at 23% of chord. Thus the 1907 Flyer had a reduced negative static margin of -10% compared to the 1908/1905 Flyer with a static margin of -13%. The reduced negative static margin of the 1907 Flyer would manifest itself as slightly reduced pitch instability. Orville discussed the improved longitudinal flying qualities of the 1907 Flyer with two people aboard and the resultant forward CG in a 1908 letter to Wilbur, "I noticed...that there did not seem to be any too much surplus pressure on the underside of the rudder [stabilizer]. It seemed, however to make the flight steadier than when I was on board alone." [Ref. 3]

3. Lateral - Directional Stability and Flying Qualities

As can be seen in Figure 3 the 1903 Flyer had anhedral. This was in fact an aircrew centered design choice based upon the Wright brothers' gliding experiences. The 1902 glider was originally rigged with zero dihedral. It had weak directional stability as did subsequent Wright gliders and Flyers. It also had a slight positive dihedral effect. The

weak directional characteristics would not turn the glider into a crosswind gust. In close proximity to the ground (i.e., the hills at Kittyhawk) when in a crosswind gust, it was found that the downwind wingtip would catch the ground as the glider rolled away from the sideslip, due to the positive dihedral effect. To prevent this, they rigged the 1902 glider with anhedral to avoid snagging the downwind wingtip on the dunes. [Ref. 3]

The anhedral also caused a degree of roll instability which aided wing warp control effectiveness. The anhedral and weak directional stability combined to create an unstable spiral mode in the early Wright Flyers. The spiral mode of the 1903 Flyer had a very short time to double amplitude of approximately 2.5 seconds. The roll acceleration was heavily damped and yielded a short time to steady state roll rate. The Dutch roll period was relatively long at approximately 4.5 seconds due to the low speed and the low directional stability compared with the yaw inertia. These characteristics were tolerable during the early glides and powered flights which were essentially straight-line.

From an aircrew centered design point of view, the anhedral was helpful during the early straight-line flights. It helped prevent the downwind wingtip from catching the hill. However, the unstable spiral mode which resulted from the anhedral and weak directional stability caused a number of crashes when the Wrights began to attempt turning flight in late 1904. During September they had several incidents and crashes which they noted in their diaries with the amplifying comment: "unable to stop turning". They correctly analyzed the anhedral as the problem and they re-rigged the Flyer to eliminate anhedral as seen in Figure 11. [Ref. 3]

With the elimination of wing anhedral, they were able to perform sustained turning flight. Wilbur wrote in his diary "...celebrated Roosevelt's election by a long flight and went around four times in 5 minutes 4 seconds." [Ref. 3]. This is also at a turning rate well above the current Standard Rate Turn of two minutes for a 360 degree turn.

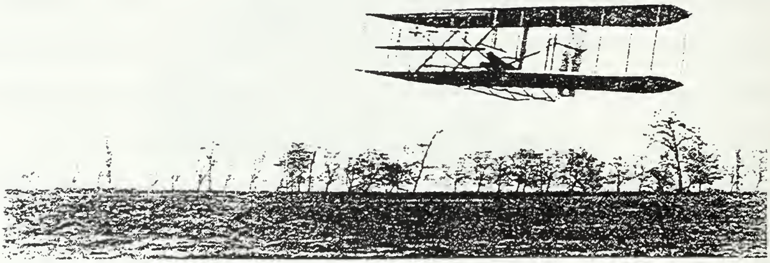


Figure 11. 1904 Wright Flyer Rigged Without Anhedral. From Ref. [3].

Turning flight while now possible, was still difficult. On one occasion, Orville crashed while he was so concentrating on turning, that he (in current terms) lost situational awareness, neglected pitch control and ended up in a pitch departure. The primary problem in roll was adverse yaw, which generated a sideslip. Wilbur had first noted and recorded adverse yaw in 1901. The adverse yaw was caused by wing warping for roll control. The wing warp was actuated by a hip girdle shifted laterally by the prone pilot. The hip girdle was also proportionally interconnected to the rudder. In this way a yaw input was made as a roll was commanded. However, this method of countering the sideslip caused by adverse yaw was not adequate given the low directional stability and weak yaw control power. At only one low airspeed would adequate rudder be commanded to eliminate the sideslip. At lower airspeeds the rudder control power was too low to correct the sideslip because of the reduced dynamic pressure. At higher airspeeds, the adverse yaw generated was greater than rudder compensation, despite greater dynamic pressure. In an

evolutionary aircrew centered system design fashion, the Wright brothers would eventually discard the proportional mechanical interconnected rudder to wing warp in favor of a three axis control system.

4. Flight Control Systems of the Wright Flyers

The Wright brothers were the first to master turning flight through an aircrew centered design process coupled with test and evaluation. They recognized that a roll input was needed to establish banked, turning flight and that a rudder input was essential for minimizing sideslip. They were thus unique among their contemporaries: Lilienthal and other glider pilots used dihedral and weight shift for lateral control and equilibrium while Voisin of France attempted to skid around turns on rudder only in his powered airplanes. This roll and rudder input concept was the basis to the Wright brothers' patent for the invention of the airplane. They applied for the patent in 1902. It was granted in 1906.

The early Wright Flyer control mechanization was a fore/aft moving control stick in the left hand for elevator control, and wing warp interconnected to rudder through the hi girdle described above. By August 1905, they recognized the need to independently control wing warp and rudder deflection. The solution was to retain elevator control in the left control stick and hip girdle for wing warp. The proportional interconnection controlling the rudder was replaced with a control stick in the right hand. The right hand controller moved longitudinally to create the rudder inputs. Despite the obvious transformation of left and right rudder being commanded by fore and aft control stick movement, the Wright brothers could now vary the amount of rudder applied to balance the adverse yaw due to wing warp. Using this control system in September and October 1905, they mastered stall recoveries and learned to avoid turning stall by lowering the nose to increase airspeed to compensate for the increased g load on aircraft and the loss of vertical lift component due to bank angle. On October 5, 1905 they flew for 38 minutes. As Culick and Jex wrote "What a magnificent achievement! In the seven days from September

28, 1905 to October 5, 1905, the Wright brothers solved their last serious problem and had a practical airplane." [Ref. 3]

With sustained and controlled flight proven, they then felt ready to proceed with marketing their Flyer. They were not to fly again till 1908, due largely to their bitter patent infringement lawsuits with other airplane experimenters, most notably Glenn Curtiss. [Ref. 3]

When they did start flying again in 1908, it was with considerably revised airplanes. The 1907 Flyer and 1908/1905 Flyer featured upright seating for two, more powerful engines (30 horsepower on the 1908/1905 Flyer) and a new control system. The hip girdle was eliminated due to the upright seating. Roll control was actuated through the right hand control stick. The right control stick now moved left and right for wing warp and fore/aft for rudder. The left control stick was retained for elevator control. The 1908/1905 Flyer was taken to Kill Devil Hill in 1908 to allow Orville and Wilbur to refresh flying skills after a two and one-half year hiatus, and to allow familiarization with the new control system. Both Orville and Wilbur each got approximately 15 minutes of flight time, before crashing. During this flying period, each brother flew with a passenger. Wilbur later sailed for France with the repaired 1908/1905 Flyer to demonstrate the airplane to a European audience. The first public flight demonstration was performed by Wilbur in France, followed shortly by Orville in Washington D.C. It is a testament to their skill, and the controllability of the aircraft that after a two and one-half year layoff from flying that they could fly at all. [Ref. 3]

Despite their efforts at aircrew centered systems design, with changes and improvements, the Wright Flyer was still a challenge to fly. Wilbur had three short flights during his demonstration tour in France, and wrecked his machine on the third landing. He wrote to Orville, "I haven't yet learned to operate the handles without blunders." From a human factors point of view, one must say "Small wonder!"

D. CREWSTATION DESIGN OF THE WRIGHT FLYER

1. General

The pilot was located on the aircraft's centerline. This appears to have driven engine placement and wing design. The engine is located to the right of the pilot. The right wing is 4 inches longer than the left to compensate for the weight of the engine.

2. Prone Pilot Position

The early Wright Flyers are distinctive because of the prone pilot position. This was partially a carry over from the practice of their gliding days. While they had chosen control surfaces and not weight shift for control and equilibrium, they did of course take advantage of moving fore and aft in the prone position for longitudinal trimming of the gliders. The prone position afforded less drag compared to any upright seating position. This was important for gliding performance and later for the low powered early Flyers. The Flyers had a greater range of center of pressure travel than the gliders because the Flyers featured a reflexed airfoil with linen covering on both upper and lower surfaces. The gliders had linen covering only on the airfoil upper surface. This in turn generated stronger pitching moments for the Flyers than for the gliders. The longitudinal shift of pilot weight could not compensate for these pitching moments or even be of much help in trimming them out. The prone pilot position thus was retained on the powered Flyers for drag reduction. The Wright brothers adopted upright seating only when more powerful engines were developed to overcome the increased drag of the seated position relative to the prone position.

3. Drag Penalties for Seated and Prone Pilots

Hooven [Ref. 3] cites drag figures from the 1/6th scale wind tunnel tests reported by Bettis and Culick. The drag without a pilot was found to be 125 pounds at the historic airspeed of 44 feet per second (26 knots or 30 miles per hour). The total drag for the Flyer and pilot must be computed in order to estimate the power required.

The classic incompressible drag equation can be used to compute the drag contribution of the pilot:

$$D = \frac{1}{2}\rho V^2 C_D S \qquad \text{(Equation 1)}$$

Hoerner [Ref. 4] cites an equivalent drag area (C_DS) of 1.2 square feet for a prone man. For the prone pilot at 44 feet per second and standard day density, his drag contribution would be:

$$D_{prone} = \frac{1}{2}(0.002378)(44)^2 1.2 = 2.8 \ pounds$$

The total drag for the Flyer and pilot can now be obtained by summing the two drag contributions:

$$D = D_{Flyer} + D_{prone} = 125 + 2.8 = 127.8 \ pounds$$

The relationship of thrust (T), velocity (V) and horsepower required to maintain level flight is given by:

$$HP = \frac{TV}{550} \qquad \text{(Equation 2)}$$

Using the above equation and setting thrust equal to drag (D) for level, unaccelerated flight at 44 feet per second yields a level flight horsepower required value:

$$HP = \frac{DV}{550} = \frac{127.8 \, x \, 44}{550} = 10.2$$

Due to losses at the propellers and in the chain drive, this level flight horsepower requirement would necessitate a higher power output for the engine. The overall efficiency ratings account for the various losses and permit an estimation of the engine power output necessary. The overall efficiency rating to be used here is of the form:

$$\eta_{overall} = 100\% - (\%Losses_{prop} + \%Losses_{xmsn}) \qquad \text{(Equation 3)}$$

The Wright brothers estimate of overall efficiency was 66%, which included a 10 - 15% loss in the chain drive. The true losses according to Hooven [Ref. 3] were probably 5%. To arrive at a more reasonable value for overall efficiency, one must use realistic chain drive losses and also calculate the losses due to propellers.

Assuming the low side of the Wright brothers' chain drive loss estimate of 10%, one can obtain the propeller losses using Equation 3:

$$66\% = 100\% - (\%Losses_{prop} + 10\%)$$

$$Losses_{prop} = 24\%$$

Assuming the Wright brothers' high side drive loss estimate of 15% the propeller losses can be estimated using Equation 3 as:

$$66\% = 100\% - (\%Losses_{prop} + 15\%)$$

$$Losses_{prop} = 19\%$$

Thus the overall efficiency, using the above estimated propeller losses and the 5% figure for transmission losses, can be estimated to be:

$$\eta_{overall,low} = 100\% - (24\% + 5\%) = 71\%$$

$$\eta_{overall,high} = 100\% - (19\% + 5\%) = 76\%$$

The efficiencies computed can be compared with the efficiencies resulting from the engine power analysis of Hooven. Hooven writes "the machine requires 13.8 horsepower [engine power output] for level flight at 30 miles per hour [44 feet per second] which means that their engine must have turned out more horsepower than the Wrights' tests had shown." By recognizing two factors at play, one can account for this higher engine power output than the historically accepted value of 12 horsepower . The first Flyer engine was tested at an earlier date in 1903 in Ohio, but was flown during a cold December of that year at Kill Devil Hill. The engine power would be greater (fixed throttle, constant rpm) in the colder, denser air than indicated during the brake horsepower tests at warmer temperatures. Despite a water cooling system, the unjacketed valve cages and cylinder heads were air cooled. Thus the engine power output was highly dependent upon air cooling. Engine power output would be increased in flight on a cold day therefore because the engine cooling system could be more effective.

Using the 13.8 horsepower engine output figure and the 10.2 horsepower required for level flight, the overall efficiency can be calculated by use of the definition of overall efficiency, the ratio of power realized after losses versus the power produced by the engine:

$$\eta_{overall} = \frac{Power\ realized\ (after\ losses)}{Power\ produced\ by\ engine}\ x\ 100\% \qquad \text{(Equation 4)}$$

$$\eta_{overall} = \frac{10.2}{13.8}\ x\ 100\% = 74\%$$

The above figure of 74% propulsive efficiency is in agreement with the range of efficiencies calculated above.

In order to assess the feasibility of upright seating in the 1903 Flyer, the seated pilot drag must be computed and added to the Flyer's drag. The increased horsepower required must be estimated and compared to the engine power available. The drag contribution of the seated pilot can be calculated by using Equation 1 with Hoerner's equivalent drag area ($C_D S$) of 9 square feet for a seated person:

$$D_{seated} = \frac{1}{2}(0.002378)(44)^2 9 = 20.7 \ pounds$$

The drag for a seated pilot is over seven times greater than for a prone pilot. The drag for the 1903 Flyer with a seated pilot would be the sum of aircraft and pilot contributions:

$$D = D_{Flyer} + D_{seated} = 125 + 20.7 = 145.7 \ pounds$$

The horsepower required to sustain level flight at 44 feet per second with a seated pilot would be:

$$HP = \frac{145.7 \ x \ 44}{550} = 11.7$$

The engine power thus would have to have been the horsepower required for level flight divided by the overall efficiency:

$$HP_{eng} = \frac{HP}{\eta_{overall}} = \frac{11.7}{.74} = 15.8$$

This engine power requirement for a seated pilot is 32% greater than the Wright brothers static test indicated was available and one must conclude was not attainable in 1903. Even Hooven [Ref. 3] assumes a maximum of 15 horsepower initial power output, dropping to 13.8 horsepower within 10 seconds for his simulation of the flight characteristics of the Flyer. The 1904 engine, with a full years' development was rated at 16 horsepower, just up to the required power output required for flight with a seated pilot. It was however still flown from the prone position.

The drag penalties for two seated people as in the 1908/1905 Flyer and the 1907 Flyer would have been twice that for one seated, as they were shoulder to shoulder and would have little interference drag. The total drag on the Flyer with two seated occupants would have been:

$$D = D_{Flyer} + (2\ x\ D_{seated}) = 125 + (2\ x\ 20.7) = 166.4\ pounds$$

To fly at the same 44 feet per second with a seated pilot and passenger aboard would require:

$$HP = \frac{166.4\ x\ 44}{550} = 13.2$$

The engine power needed to provide the horsepower required and overcome the losses of propeller and transmission would be:

$$HP_{eng} = \frac{13.2}{.74} = 18$$

This engine power was 50% greater than the power rating of the 1903 engine, and was unattainable. The prone position of the Wright Flyers was largely dictated by the limitations of engine power available. The later 30 horsepower engine of the 1908/1905

Flyer and 25 horsepower 1906 engine in the 1907 Flyer would have certainly been capable of sustaining level flight with upright seating for pilot and passenger.

E. FOCUS ON AIRCREW CENTERED DESIGN ASPECTS

The most visually striking pilot centered aircraft design detail of the early Wright Flyers is the prone pilot position. The early Flyers required all the power produced by the engines just to sustain flight even at the much lower drag values of the prone pilot relative to a seated pilot. The Wright brothers could only attempt upright seating and passenger operations once more powerful engines were developed. The evolution to upright seating was necessary for the Flyer to become a practical airplane capable of longer flights, demonstration flying, and the training of other pilots.

The control system also evolved in concert with the change in pilot position. The upright position with passengers led to discarding the hip girdle for roll and yaw control. The ability to control each axis independently was necessary to afford the pilot command over the airplane.

The Wright brothers capitalized upon the aircrew centered system design changes possible as the aviation technology matured, and made necessary improvements to the Flyers as their experience increased.

III. SPIRIT OF ST. LOUIS

A. DESIGN PHILOSOPHY FOR THE "SPIRIT OF ST. LOUIS"

The Spirit of St. Louis shown in Figure 12 was point designed to the specifications of Charles A. Lindbergh for long distance solo flight. In particular, it was designed to compete for the $25,000 Orteig prize, which had been offered in 1919, for the first non-stop flight between Paris and New York. Should the Orteig prize be won by another, the back-up mission envisioned by Lindbergh was a trans-Pacific flight to Hawaii. [Ref. 5]

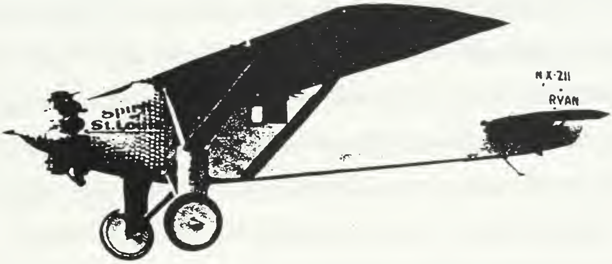


Figure 12. Spirit of St. Louis. From Ref. [7].

Lindbergh was a 25 year old airmail pilot with approximately 2000 flight hours in 1927 when he began to formulate plans for the trans-Atlantic flight. The Orteig prize was well known, having been unclaimed despite several attempts. One of the major problems which he perceived with contemporary attempts for the New York - Paris flight was the use of large multi-engine aircraft with crews of up to four; pilot, copilot, navigator and mechanic. He felt that a navigator was unnecessary for a dead reckoning task, and that a modern airplane with good reliability would not need a flight mechanic. Lindbergh had always preferred to be alone, both in boyhood and in aviation, and did not believe a copilot was necessary. The weight of additional crewmembers would require more fuel than a single pilot to attain the desired range. To accommodate additional crew, fuel volume and

weight, the aircraft gross weight would increase due to being a larger airplane both in fuselage and wing size. Many of the competing aircraft were biplanes, with a correspondingly greater drag and thus higher fuel requirements than monoplanes. Lindbergh saw all of these factors as being significant disadvantages due to the increased weight and drag which added to the fuel requirements.

Additional crew, fuel volume and fuel weight led to an airplane which was large and heavy enough to require multiple engines to provide adequate takeoff power. Compared to a single engine design, the multi-engine layout had increased drag and fuel requirements, while adding the weight of the additional engines. The carriage of the additional engine weight required still more fuel, and thus higher aircraft weight. The engines of the time did not have sufficient power to sustain flight for the multi-engine aircraft should one of the engines fail. The multi-engine airplanes of the era had more than one engine because they needed all the power of the combined engines for normal operations. Lindbergh thus believed that the multi-engine planform provided no redundancy and offered no significant safety advantage. Lindbergh believed that the optimum solution was the selection of a single place, single engine monoplane, using one of the new 220 horsepower Wright Whirlwind J5C-9 radial engines which had demonstrated great reliability. [Ref. 6]

B. DESIGN AND MANUFACTURE OF THE SPIRIT OF ST. LOUIS

Lindbergh secured the financial backing of nine prominent St. Louis businessmen, and together with his own savings, had a budget of $15,000 with which to work. The greatest initial hurdle was finding an airframe manufacturer willing to build an airplane for the venture. Most regarded the whole effort as foolhardy and would not even be associated for fear that their firms' name would be discredited through involvement with a harebrained stunt destined to fail. The only company which was willing to participate was Ryan Airlines of San Diego, CA. Control of Ryan Airlines had recently been bought by a new owner, Mr. Benjamin Franklin Mahoney. Only a few days before agreeing to build the

aircraft Lindbergh desired, Mahoney had hired Donald Hall, a young aircraft engineer. Hall was to be the chief engineer with primary responsibility for the design of the Spirit of St. Louis. The airplane was to be designed and built in 60 days. [Ref. 6]

While Hall was the chief engineer, Lindbergh was intimately involved in the design process. "All of the various items of design had very careful consideration, in which Colonel Lindbergh took a prominent part." The Spirit of St. Louis is often cited as being a modified Ryan M-2 mail plane. Hall states that the original plan had in fact been to modify the standard M-2. However, after Lindbergh arrived and presented his specifications, Hall "quickly determined that modification of the M-2 was less practicable than redesign. The airplane was then laid out anew...". The design of the Ryan NYP (New York to Paris) which resulted was in fact, aircrew centered, in that the M-2 had to be redesigned to comply with Lindbergh's desired pilot location. Lindbergh's basic specifications to Ryan Airlines included the following four requirements:

1. The airplane was to be a monoplane
2. It was to be powered by a single Wright J5C-9 Whirlwind engine
3. "Good power reserve on takeoff" with over 400 gallons of fuel
4. Pilot was to be seated aft of all fuel tanks "for safety in forced landing "

The fuselage was lengthened to allow the most unique design aspect, a fully enclosed cockpit aft of the fuel tanks. Lindbergh specified this aft cockpit location because his analysis indicated that this provided the greatest likelihood of surviving a forced landing. This cockpit location aft of all fuel tanks avoided the potential of having the pilot doused by gasoline from a ruptured tank and being subsequently burned. However, this cockpit location as shown by the side windows in Figure 13 prevented any forward field of view. No forward field of view is clearly a hazard for operation in congested airspace, or at low altitude. Lindbergh was willing to accept the compromise to the forward vision in order to reduce fuselage cross section by eliminating a pilot station protruding above the fuselage streamlines. The Spirit of St. Louis was of course being point designed to fly across the

open Atlantic Ocean, where no other aircraft were operating. The reduction in fuselage cross section, and elimination of a canopy or windshield translated to lower drag and therefore less fuel required for the mission profile. [Ref. 7]

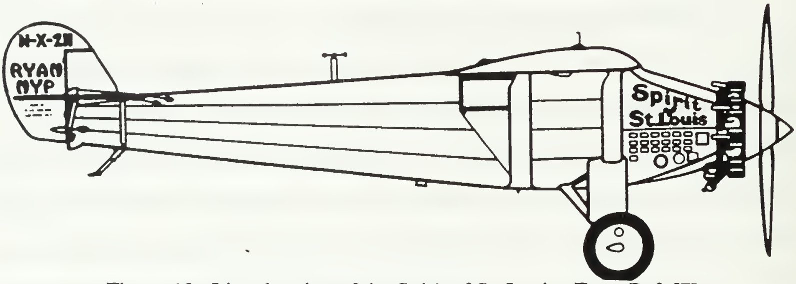


Figure 13. Line drawing of the Spirit of St. Louis. From Ref. [7].

A periscope to permit a degree of forward field of view was proposed by a Ryan Airlines employee, a Mr. Randolph who had considerable submarine experience. This suggestion was accepted by Lindbergh with the proviso that if he found it aerodynamically disadvantageous, or not satisfactory it would be removed. The periscope was on the instrument panel and provided a forward view by a 3 inch by 5 inch retractable mirror projecting from the left side of the fuselage. Hall writes: "The device proved of no disadvantage aerodynamically on account of the retractable feature, and was of certain utility during the flights of the airplane." [Ref. 7]

The periscope was an aircrew centered design element which permitted some forward view in cruise flight, however it's utility was exaggerated. Lindbergh himself commented on the periscope, refuting inaccurate newspaper reports that he would takeoff and land using the periscope. He had told the reporters that he only intended to use it in low level cruise flight, looking for obstacles to flight. He writes: "It would have been impossible to takeoff and land looking through that periscope." Most of the aircraft of the era, particularly the mail planes which Lindbergh had flown extensively, were tail skid or tail wheel configured with fuselage blocking the pilot's forward view during the nose high

operations of taxi, takeoff, and landing. Pilots learned to S turn or sideslip to check for hazards in order to compensate for the restriction to forward field of view. [Ref. 6]

The increased aircraft weight due to the required fuel load led to a wing design change in span and structure. The wingspan was increased by 10 feet over a standard M-2 wing. Compared to the M-2 design the aileron area was reduced, and the ailerons were relocated inboard from the wing tips. This was due to the increased moment arm relative to the M-2 and was "expected to reduce wing tip deflection and give better aerodynamic efficiency." [Ref. 7]

In order to provide the range which Lindbergh specified, the fuel system was designed to provide capacity for 425 gallons of gasoline. It consisted of three wing tanks, one center and two outboard, and two fuselage tanks arranged in tandem. The fuselage tanks were located behind a 25 gallon engine oil tank, which was designed to act as a firewall between the engine and fuel cells. All the gasoline tanks were connected to a Lunkenheimer distributor in the cockpit. It was possible to pump from any tank to any other. The fuel system had two fuel lines to the engine to provide a redundant fuel flow path. [Ref. 7]

Hall understood Lindbergh's rationale for specifying a single place design. Compared to a two place configuration, the "...fuselage could be shorter and lighter: the plane could carry another 350 pounds of gasoline." Lindbergh prized additional gasoline more than another crewmember. [Ref. 7]

The Spirit of St. Louis was designed in an aircrew centered fashion for one particular pilot's weight and size. The weight allowance for the pilot was precisely Lindbergh's own weight, 170 pounds. Since he was located in the tapering section of the fuselage, a hollowed out area was formed in the overhead to accommodate his head. [Ref. 7]

In addition to the aforementioned weight savings, several other design compromises were struck to save weight. No radio was to be installed. Lindbergh had

found them to be unreliable; when one most needed them in foul weather, they did not work. In fair weather they worked fine, but were not needed. The omission of a radio saved 90 pounds. No parachute was to be carried, which saved 20 pounds. The pilot's seat was a specially cut down wicker chair. No night flying equipment or position lighting was installed. No fuel gauges were installed; Lindbergh found that they were "heavy and rarely worked". He preferred to set engine RPM, measure elapsed time on his grandfather's watch and using the relationship between RPM and fuel burn rate, compute the fuel consumption. No sextant was to be carried. Lindbergh felt that he would not be able to fly and take celestial observations at the same time. No fuel dump valves were incorporated in the fuel tanks. He designed and had made a set of lightweight flight boots which saved several ounces. He removed the spare pages from his notebook and cut out the sections of his navigation charts where he did not plan to be. His rations allowances included five sandwiches and one gallon of water, with emergency rations and another gallon of water. Lastly, he turned down a $1000 offer from a stamp collector to transport a pound of mail to Paris. Lindbergh recognized and articulated the weight versus safety dilemma in the design process: "Safety at the start of my flight means holding down the weight for takeoff. Safety during my flight requires plenty of emergency equipment. Safety at the end of my flight demands an ample reserve of fuel. It's impossible to increase safety at one point without detracting from it at another." [Ref. 5]

C. FLIGHT TESTING THE SPIRIT OF ST. LOUIS

The Spirit of St. Louis was indeed completed for its first flight test within 60 days. Hall notes that the labor to build the NYP required 3000 man hours; 775 hours by the designer and 75 man hours by other engineers. Total cost of the airplane, including engine, was $10,580 dollars. [Ref. 7]

All flight tests were conducted at Camp Kearney, California. Lindbergh restricted the fuel loads used in testing to 300 gallons. The surface condition of the airfield was so poor that he did not wish to risk a tire puncture and subsequent aircraft damage at higher

weights. The mechanic who removed the wheel chocks to allow taxi for the first flight on April 28, 1927 was Douglas Corrigan. Corrigan was to later achieve notoriety on his own long distance flights. The Ryan NYP departed Camp Kearney at 3:55 PM on May 10, 1927 on the first long distance test flight. Lindbergh set a record for the first non stop flight from San Diego to St. Louis, 1500 miles. While enroute, over the Rocky Mountains at night, the aircraft experienced two episodes of carburetor icing which almost led to engine failure. In order to save weight, carburetor heat had not been installed. Upon arrival at Curtiss Field, New York, Lindbergh ordered a carburetor heater fitted. [Ref. 5]

At Curtiss Field, Lindbergh had an earth inductor compass installed by the Pioneer Instrument Company. Admiral Byrd graciously offered him the use of Roosevelt Field which had a 5000 foot grass runway specially prepared for Byrd's own attempt at the Orteig prize. This runway was considerably longer than Curtiss Field's, Lindbergh accepted. While Lindbergh waited for the weather to break, Harry Guggenheim inspected the Spirit of St. Louis. Guggenheim had been a WW I Navy pilot and was the trustee of the Daniel Guggenheim Fund for the Promotion of Aeronautics. He felt that the cockpit was too small. Lindbergh's response was that it had been tailored (in what could now be considered an aircrew centered design methodology) for his own comfort: "the cockpit probably looked cramped since it was designed to fit me closely. Actually there was plenty of room for the pilot, more than in most planes of the time - an essential item for long distance flying." [Ref. 5]

Lindbergh found that the fuel tank capacity was greater than Hall had calculated. The tanks held an additional 25 gallons or 125 pounds of fuel which translated to 160 miles of added range. The oil consumption was found to be lower than anticipated, Lindbergh saved 35 pounds on oil. The design mission gross takeoff weight was 5135 pounds. With the additional fuel and reduced oil, the NYP weighed 5250 pounds. Lindbergh accepted the additional 115 pounds (2.2% increase) over design gross weight for the added range which it provided. [Ref. 5]

D. NEW YORK TO PARIS FLIGHT

The measure of success of the Ryan NYP design was the New York to Paris flight. The morning of May 20, 1927 broke with low ceilings and a slight tailwind at the takeoff position of the Spirit of St. Louis. Lindbergh did not want to risk overheating the engine in taxiing to the other end of the field. The recent rains had left the sod runway very muddy and soft. Towing the airplane to the other end of the runway would have required defueling the airplane to prevent it and the tow truck from bogging down. The lost time would cost him his desired before sunset arrival in Paris. Taking off to the west would also point him towards housing developments, endangering the occupants should he crash after takeoff, a risk which he did not want to accept. Additionally, a westerly departure was off his desired flight path and would cost several miles of potential range by the time he was turned and on track. Lindbergh accepted the tailwind condition for an easterly departure and started the engine. A mechanic held a booster coil which provided a hotter spark for the engine to start on the cold, damp morning. Once started, the wires to the booster coil were cut and the coil was removed to reduce the weight carried. [Ref. 5]

With the over gross weight condition and the tailwind, Lindbergh cleared the wires at the departure end of Roosevelt Field with approximately 20 feet to spare [Ref. 7]. Inflight, Lindbergh was greatly affected by fatigue as he had not slept the night before the takeoff. The aircrew centered design compromises to accommodate Lindbergh and his mission requirements had degraded the Ryan NYP's flying qualities to the point where alert piloting was essential. The Spirit of St. Louis was unstable and required continuous attention to keep flying. Lindbergh reported that the "airplane could not be left alone for even a period of five seconds." [Ref. 6] On several occasions, he would wake from dozing to find the airplane in unusual attitudes and in extremis, requiring immediate recovery control applications. The airplane had removable glass windows on the sides of the cockpit, which he planned to insert in flight to improve streamlining. Lindbergh was

concerned doing so would quiet the engine's noise, eliminate the sensory cue of passing air and allow the cockpit to warm up and thus promote falling asleep. [Ref. 6]

The cockpit location with the head bump-out was perhaps too closely tailored to Lindbergh's physique at sea level, static conditions. At one point while at 10,000 feet altitude, he noticed his head hurting. The air cushion on which he was sitting had expanded due to the altitude, and forced his leather helmeted head against the top of the cockpit. [Ref. 6]

The need for sleep seemed to leave him with landfall over Ireland. Due to delays in flight, Lindbergh arrived over Paris after sunset. By this point, he was again experiencing the weariness of sleep deprivation. Thus his first night landing in the NYP was in a greatly fatigued condition upon arrival at Le Bourget. At this point, despite navigational errors and excess fuel used over the North Atlantic, he still had enough fuel to press on to Rome. The stories of his tumultuous reception are legion. [Ref. 5]

After landing in Paris, it had been Lindbergh's intent to continue eastward around the globe. He felt it would be an insult to the airplane to return the Spirit of St. Louis to the United States by ship. However, President Coolidge sent a cable offering passage on the U S Navy cruiser *Memphis*. Myron Herrick, the Ambassador to France advised Lindbergh that as Lindbergh was a Captain in the Air Reserve and the offer came from the Commander - in - Chief, it probably should not be declined. In any case, Lindbergh and his backers had only $1500 remaining of their original budget: the President's offer was accepted, and after the short flight to England via Belgium with more jubilant receptions, the Spirit of St. Louis returned to the United States from Gosport in the hold of the *Memphis*. [Ref. 5]

E. SPIRIT OF ST. LOUIS'S FURTHER AIR TOURS

After returning to the United States and all the jubilant celebrations, Lindbergh embarked on a highly ambitious 48 state tour. The purpose of this Guggenheim sponsored tour was to promote aviation as being practical and safe. The tour stopped in all 48 states,

spanned three months and covered 22,000 miles. The tour further confirmed the validity of Lindbergh's aircrew centered design for long distance solo flight. Lindbergh insisted on timely arrival and not missing scheduled events for any reason in order to demonstrate the reliability and coming of age of aviation for dependable transportation. Promotion of aviation and encouraging the construction of airports and airways navigation systems were the major themes. [Ref. 7]

The Spirit of St. Louis made two more major flights. Dwight Morrow, Ambassador to Mexico and the President of Mexico, Plutarco Calles invited Lindbergh to Mexico City. Taking off from Washington D.C. on December 13, 1927 he flew for over 27 hours, arriving in Mexico City only two hours late. He was greatly upset by his late arrival, particularly for the inconvenience to the honor guard troops in full dress parade regalia. The lateness was due to the very poor quality maps of Mexico available to him and navigation problems resulting from their use. It was in Mexico City that Lindbergh met the Ambassador's daughter, Anne Morrow, who would later become his wife. [Ref. 6]

The final major tour of the Spirit of St. Louis was Lindbergh's Central, South America and Caribbean tour which ended in St. Louis. On the return leg from the Caribbean to Florida, Lindbergh experienced a several hours long period during which he had a navigation malfunction. Both his earth inductor compass and standby magnetic compass were spinning and of no value. The best which he could manage was observing that the compasses seemed to slow their rotation on one particular quadrant. This he judged to be a sign that they were at least getting some influence from the earth's magnetic field. He attempted to judge his heading based on the slow area of compass spin. Instead of making landfall over southern Florida, he arrived over the Bahamas. This event together with the poor quality of maps available, led him to feel that some of the major aircrew centered challenges for making aviation practical were the development of airborne navigation systems and improving aeronautical cartography. [Ref. 7]

A recurring problem for Lindbergh on the tours was the lack of wheel brakes on the Spirit of St. Louis. The landing gear configuration was conventional for the time with main wheels forward of the center of gravity and a tail skid, a "taildragger". This was common practice in the era and suited lightness and simplicity requirements. No wheel brakes were installed. The tail skid provided a modicum of braking in grass and sod. The landing gear configuration proved to be a hazard during ground operations with the overly enthusiastic spectators and press. On several occasions, Lindbergh had to kill the engine to avoid having anyone in the spinning propeller arc. At least once he had to execute a ground loop to keep the propeller away from the groundlings. He mentions having earlier seen a man cut in half by a propeller, and certainly did not want to have it occur on his watch. Aside from the immediate tragedy of such an event, Lindbergh was absolutely committed to having the tours demonstrate the potential safety of air travel. This sort of mishap with all the media attention could do more harm than any good he might achieve. [Ref. 6]

Lindbergh believed that the Spirit of St. Louis was becoming an important icon of safe aviation to the public. He recognized that continued operation of the airplane exposed it to the possibility of an accident of some sort. Lindbergh was very concerned about the “detrimental affect on aviation” such an accident would have. He decided to retire the Spirit of St. Louis and accept the Smithsonian Institution's request to display her. The final flight of the Spirit of St. Louis was on April 30, 1928 landing at Bolling Field, Washington, D.C. one year and two days after her first flight. The Ryan NYP was donated to the Smithsonian for permanent display. [Ref. 6]

The Spirit of St. Louis was designed and built to accommodate only the pilot. It’s passenger carrying capability was of course negligible. During the flying career of the Spirit of St. Louis, Lindbergh did manage to give three people demonstration flights. His mother flew as passenger during a stop in Grand Rapids, Michigan on the 48 state tour. Henry Ford flew as a passenger in Dearborn. Ford had never flown in any airplane, not even in the Tri Motors which were being built by his company. The other directors were

shocked and dismayed at the prospect of Henry Ford going up in this experimental barnstorming airplane. Lindbergh reported that Henry Ford quite enjoyed the flight, looking down at his factories and estate in Dearborn while perched on the right arm of the wicker pilots' chair as Lindbergh was forced over to the left skin of the fuselage. His final passenger was the President of Mexico, Plutarco Calles. The flight was over Mexico City, the presidential palace and the floating gardens of Chapultepec. [Ref. 6]

Donald Hall recounts that "Colonel Lindbergh...[was] the only pilot who has ever flown this airplane." [Ref. 7] Lindbergh however relates that during the 48 state tour, the commanding officer of the 1st Pursuit Group, Major Thomas Lanphier allowed Lindbergh to "fly one of his pursuit planes; in return I had let him fly my Spirit of St. Louis." [Ref. 6]

F. FOCUS ON AIRCREW CENTERED DESIGN ASPECTS

The Spirit of St. Louis is a milestone aircraft for the exploits accomplished with it. The aircrew centered design of the airplane was directed to the task of safely transporting a pilot across oceanic distances. The fuselage design in concept and detail was driven by the requirements of single pilot and crash safety. Any other missions and even some flying qualities were subordinate to those requirements. The Spirit of St. Louis was highly successful for the mission intended.

IV. X-15

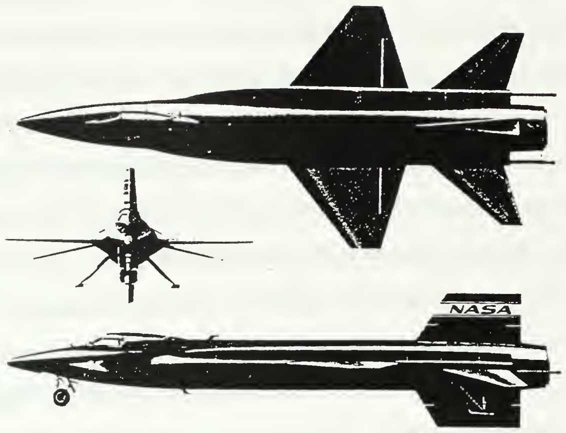
A. BACKGROUND

The X-15, shown in Figure 14, was a hypersonic, rocket propelled research airplane developed under the aegis of the National Advisory Committee on Aeronautics (NACA), the forerunner of the National Aeronautics and Space Administration (NASA). The X-15 was absolutely critical for the development of a knowledge database in hypersonic atmospheric flight. It's development was also crucial for testing and proving some of the systems needed for manned space flight. As a successful, complicated, high risk project incorporating cutting edge materials, propulsion and controls systems knowledge, it proved to be a model program for the manned space flight program to emulate. The successful integration of the pilot in an aircrew centered fashion proved to be vital for the success of the X-15 both as an aircraft and a research tool. [Ref. 8]

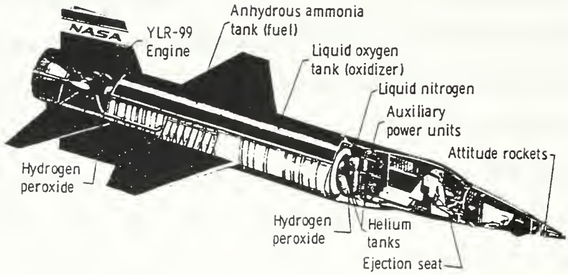
The basic concept of the X-15, a hypersonic winged glider, can in many ways trace its heritage into the 1920s. In the era when Lindbergh's "Spirit of St. Louis" was being designed, Eugen Sänger, a German rocket pioneer proposed a hypersonic winged glider as shown in Figure 15. These conceptual studies grew into the WW II antipodal hypersonic glide bomber proposals, and the supersonic glide vehicle shown in Figure 16. [Ref. 9]

B. DEVELOPMENT

In the late 1940s and early 1950s, NACA recognized that considerably more knowledge was needed in very high speed flight. In particular, the aero-thermodynamic effects on an aircraft structure were in need of study. Propulsion and control systems also needed to be explored, developed and perfected for application to the space program. NACA proposed a hypersonic research airplane. A joint project was formed with NACA, the U S Air Force and the U S Navy. The USAF released the Request For Proposal (RFP)



a. Three-view of the X-15



b. Cutaway and Interior Arrangement

Figure 14. X-15 Original Configuration. From Ref. [8].

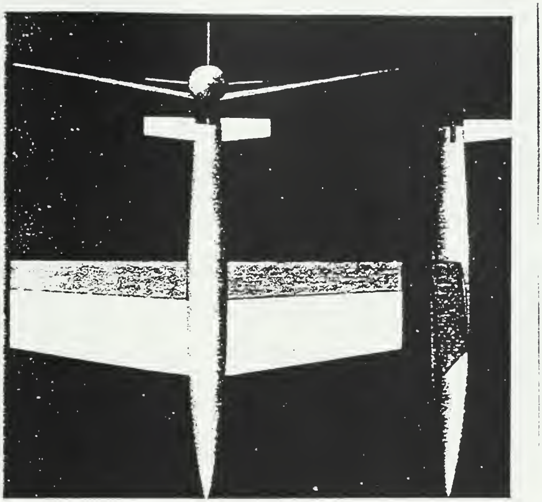


Figure 15. Sänger's 1920s Hypersonic Glider Concept. From Ref. [9].

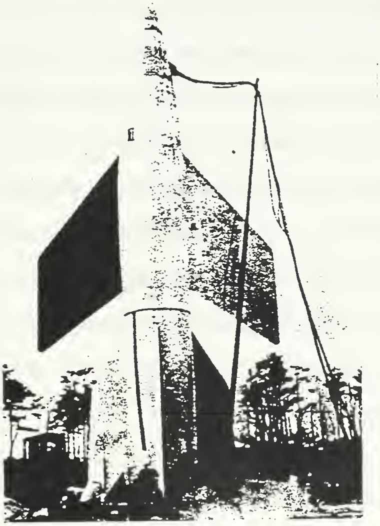


Figure 16. A-4b Supersonic Glide Vehicle. From Ref. [9].

in December 1954 calling for a manned, rocket powered hypersonic research airplane. The performance requirements were daunting, as shown by the following partial list:

1. Achieve a velocity of 6,600 feet per second
2. Flight to at least 250,000 feet
3. Representative areas of the primary structure to experience temperatures of 1200°F
4. Some of these structural portions were to have heating rates of 30 Btu per square foot per second. [Ref. 9]

The requirement for a manned aircraft was highly controversial. The usefulness of a pilot in the aircraft was hotly debated. As reported by Wendell Stillwell in a NASA report "when some scientists looked spaceward, they became concerned that man himself would be the limiting factor. Indeed...a large segment of the aeronautical industry began to speculate that man might soon be relegated to pushing buttons." The aircraft which became the X-15 was the successful North American Aviation (NAA) design in response to the Air Force RFP cited above. The first flight was on 8 June 1959, and is illustrated in Figure 17. This first flight was less than four years after RFP release and less than three years after contract award to North American Aviation. [Ref. 8]

Charles Feltz was the Chief Designer under the program management of Harrison Storms. Scott Crossfield was a veteran NASA test pilot (and former Naval Aviator) when the X-15 concept was announced. He resigned from NASA and joined NAA's X-15 design team to be the test pilot involved in design, especially cockpit design, human factors and control systems. Crossfield would be the first pilot to fly the X-15. The aircraft was an engineering tour de force in the application of very recent, cutting edge research in materials sciences, aerodynamics, thermodynamics, control systems, propulsion systems, and aircrew centered systems design.

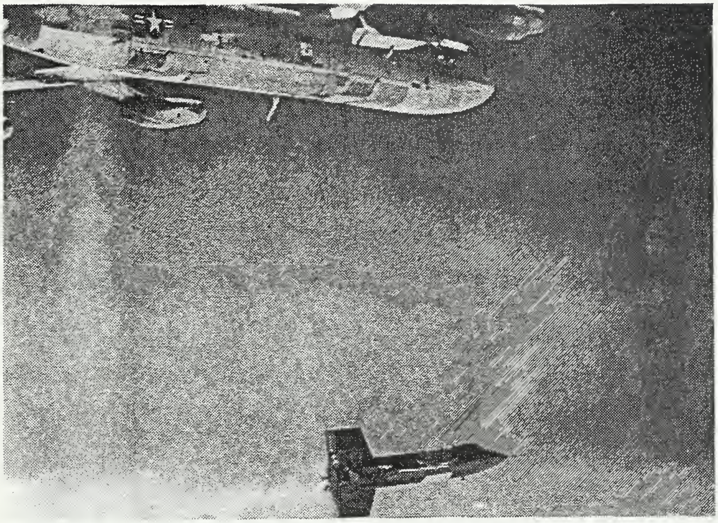


Figure 17. First Glide Flight of the X-15, 8 June 1959. From Ref. [9].

The designated engine was the Reaction Motors XLR-99. This was to be the first man-rated, throttleable rocket engine capable of air restart and was rated at 57,000 pounds of thrust. Teething problems delayed the XLR-99 availability. The first 25 flights used an interim powerplant, two XLR-11 engines arranged vertically and totaling 16,000 pounds of thrust. The XLR-11 was essentially the same engine used in the X-1 series. It used a water-oxygen fuel mixture vice the anhydrous ammonia-liquid oxygen used in the XLR-99. The X-15 bridged the gap between wing borne atmospheric flight and space flight, as shown in Figure 18. Note the relationship of the X-15 flight regime to that of the Space Shuttle (STS-4). [Ref. 8]

Research with the X-1, D-558-II, X-2 and X-3 had shown that aircraft in high speed flight have many unusual characteristics. Some were expected, such as the aerothermodynamic heating of the aircraft, while others were not as predictable, such as the change in stability and control in flight regimes above Mach 2. These included vertical

stabilizer blanking at high AOA during supersonic flight, with resulting static and dynamic instability, roll and yaw oscillations, and strong roll to yaw coupling. The oscillatory departures occurred in frequency bandwidths which were highly susceptible to pilot induced oscillations (PIO) when control was attempted. The X-15 project was to research these effects and find workable solutions.

The aircrew centered systems design not only was a critical requirement for mission success of the X-15, but also the decisions made in aircrew centered systems design, in large measure determined just how successful the research program would be. The developers of the X-15 concept were cognizant of human limitations and frailties. They were willing to accept those limitations, and accommodate the life support systems and man-rated reliability requirements necessary to place the man in the loop for augmenting flight control systems. A pilot could allow the design of a flight control system to be much simpler and thus lighter in weight. Through capitalizing upon the strengths of the pilot "the X-15 systems were made much simpler than automatic operations would have been, notably for launching, maneuvering, [and] landing." The X-15 engineers did recognize that an automatic flight control system was necessary to aid the pilot in the flight regimes susceptible to PIO. The X-15 designers "had no illusions that research pilots, no matter how well trained, could get along without aid if called upon to control a rapidly oscillating system. Neither were the pilots, for they were no less engineers than pilots." [Ref. 8]

In addition to being the active controller of the air vehicle, the pilot's other role was to be the observer of phenomena. Since the mission of the X-15 was research, the acquisition of data was a primary function and the reason for the existence of the airplane. The data acquisition and recording system weighed a total of 1790 pounds. The pilot was considered the principal payload. His weight fraction at 290 pounds of the launch weight of 33,400 pounds was 0.86%. [Ref. 10]

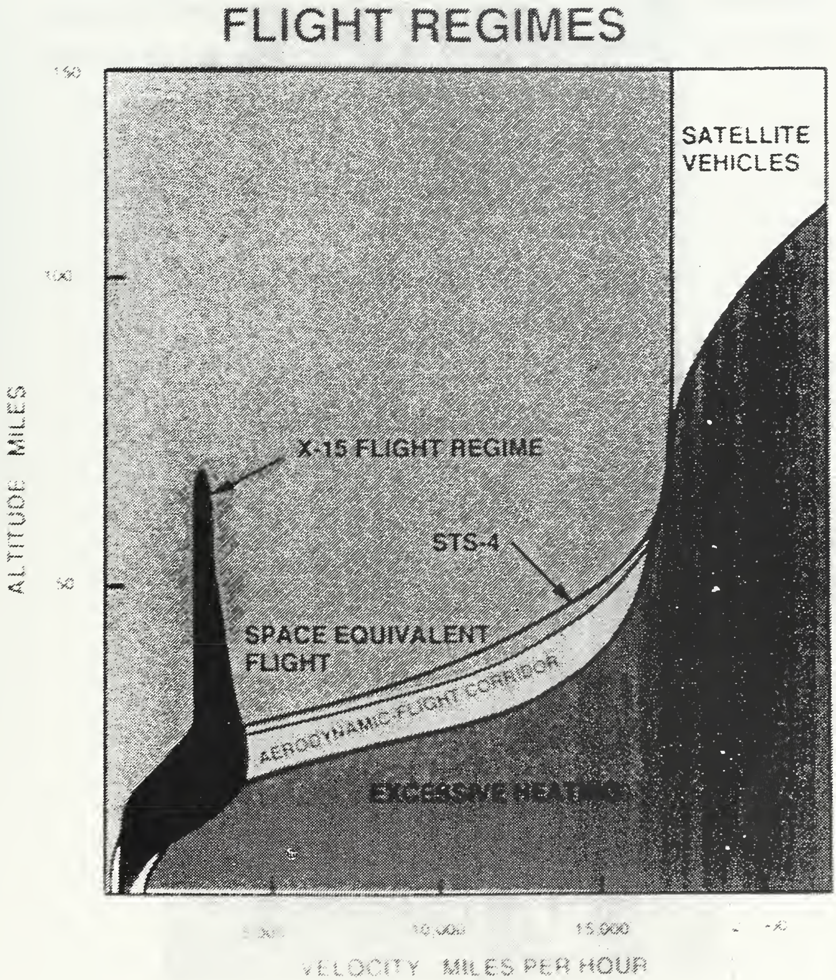


Figure 18. X-15 Flight Regime. From Ref. [9].

The X-15 exceeded the speed, altitude, and temperature requirements. Flight research was conducted using essentially two mission profiles: the near space, high altitude mission and the high speed, lower altitude mission. The high altitude mission profile is depicted in Figure 19 while Figure 20 presents a comparison of the two profiles.

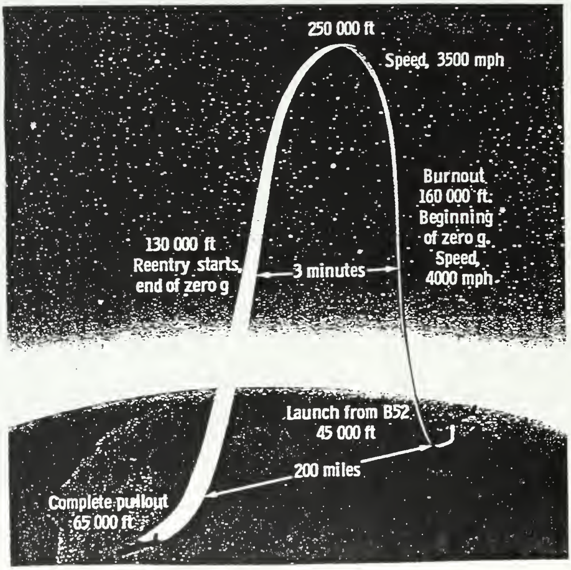


Figure 19. X-15 High Altitude Mission Profile. From Ref. [8]

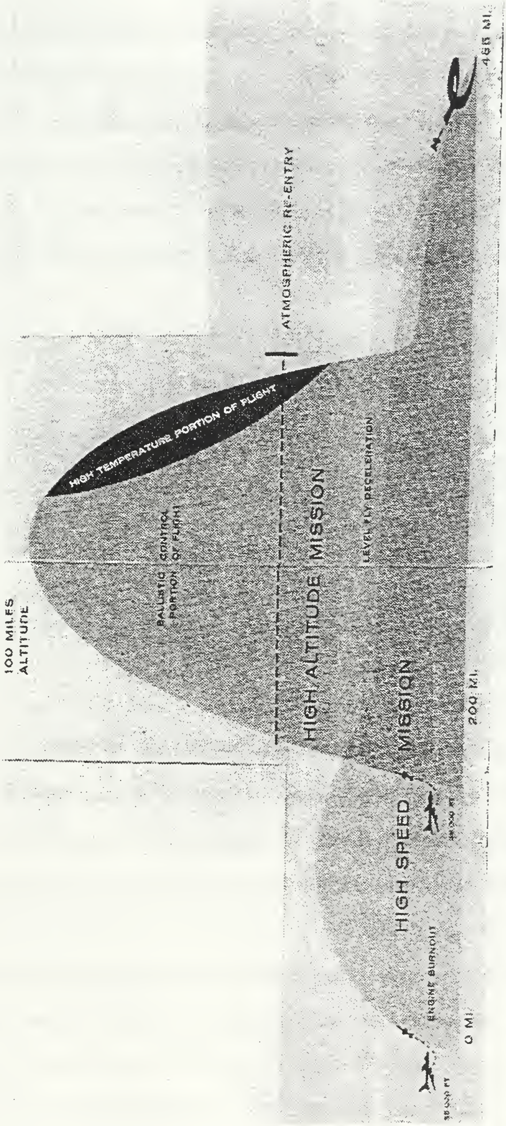


Figure 20. X-15 Mission Profile Comparison. From Ref. [9]

C. ESCAPE SYSTEM

The requirement to have a pilot aboard led to the need to protect him through the entire flight regime and provide for his safety in foreseeable emergencies. The emergency escape system of the X-15 proved to be a major technical challenge. The desired goal initially, was to provide emergency escape throughout the entire flight envelope. This proved to be technically unfeasible, and in some ways unnecessary. An analysis of accident potential during flight was conducted. The mission profile was broken down into eight phases:

1. pre-launch
2. launch and light-off
3. rocket motor burning
4. coasting
5. re-entry
6. glide
7. approach
8. landing.

The potential malfunctions in each of the flight phase and, which would lead to abandoning the aircraft were considered. The time of exposure to the flight phase was the weighting factor in calculating the probability of the malfunction. A relationship of altitude and Mach number was established and is presented in Figure 21. The greatest danger was perceived to be a propulsion system fire or explosion which would occur only during the early phases of flight. As seen in Figure 21, 98% of the accident potential was contained within a flight envelope below Mach 4.0, a pressure altitude of 120,000 feet and a dynamic pressure (q) of 1500 pounds per square foot. The distribution of accident potential can be seen as a function of mission progress. The remaining 2% of the flight envelope was largely the unboosted coast in the near space environment. The best course of action for a high

altitude emergency was to remain with the air vehicle, using the airframe for protection until lower altitudes and Mach numbers were achieved. "Low speed" for the X-15 was 2000 miles per hour or less, so an engineering challenge still existed. [Ref. 11]

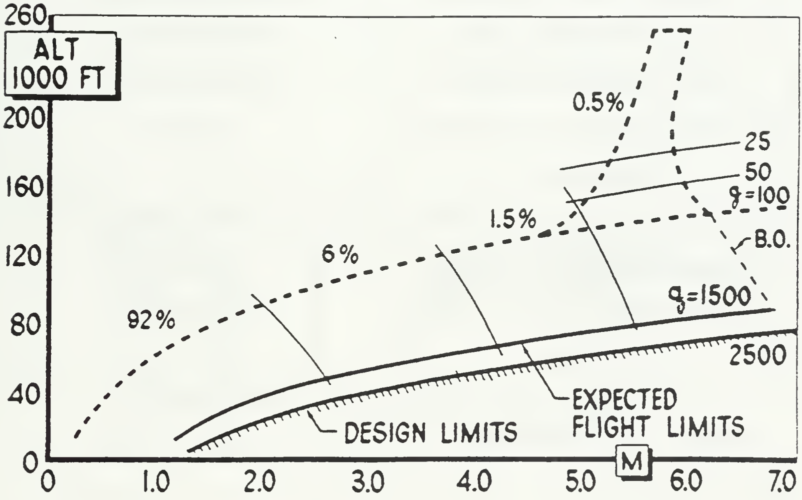


Figure 21. Analysis of X-15 Accident Potential. From Ref. [9].

With the escape envelope defined, the task was then to determine the means of escape. Four broad categories were considered: fuselage capsule, cockpit capsule, encapsulated ejection seat, and open ejection seats. These escape devices are illustrated in Figure 22. The four escape systems were evaluated for advantages and disadvantages in several comparative areas, as shown in Table I.

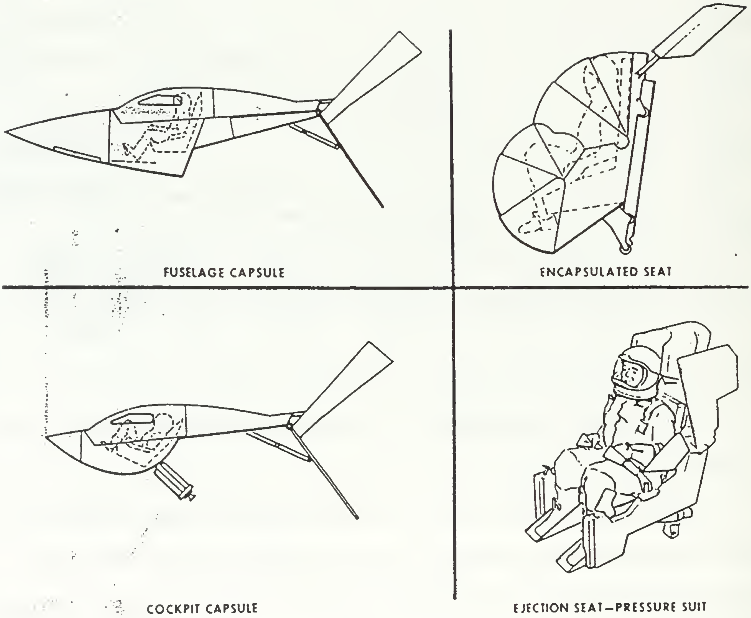


Figure 22. Escape Systems Evaluated for the X-15. From Ref. [11]

COMPARATIVE AREA	ESCAPE SYSTEM DESIGN ISSUES
Ground emergency	Precluding ejection, must permit egress
Loss of cabin pressure	Must provide secondary protection
Excessive cabin heating	Must provide secondary protection
Thermal protection	During separation and free fall
Pressure protection	During separation and free fall
Stability	Stabilization necessary after separation and during free fall
Acceleration history	Ejection system accelerations to pilot
Ground contact	Orientation and energy dissipation
Occupant egress	Encapsulated systems must provide for pilot egress

Table I. Analysis of Escape Systems. After Ref. [11]

Each of the systems had strengths and weaknesses for mission suitability. All four were intended to provide for some form of ground egress and thus required canopy jettison. Thermal protection and pressurization were to be provided by redundant systems in the fuselage capsule concept and by pressure suits for the other three. Each system was to be provided with post-ejection stabilizing. Post-ejection accelerations were least severe on the fuselage capsule and greatest on the ejection seat. The open ejection seat was still required to provide wind blast protection for the pilot during ejection, and environmental support during the descent. The encapsulated ejection systems were required to provide that energy dissipation through shock absorbing systems, without any contribution from the pilot. This incurred a weight penalty. The ejection seat system offered the advantage that the pilot separates from the ejection seat. A much smaller mass is descending with the parachute, thus lower kinetic energy was to be dissipated at touchdown. The pilot could (if

conscious) position himself to absorb some degree of the landing shock. The escape system analysis led to a comparison of complexity of the individual concepts to the mechanical reliability. Figure 23 shows the reliability/complexity tradeoff. [Ref. 11]

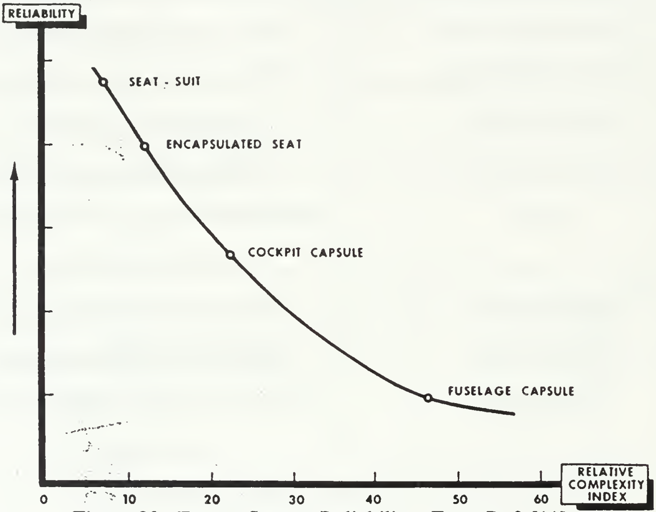


Figure 23. Escape System Reliability. From Ref. [11].

The desirability of the four escape systems was established based on four parameters: airframe compatibility, development status, weight, and mechanical reliability. Weight penalty was the most severe variable. Excess weight would penalize altitude and Mach number attained. Table II illustrates the estimated weight (including that of pilot) of

	Ejection Weight	Aircraft Weight Gain
Ejection seat	460 pounds	N/A
Encapsulated ejection seat	750 pounds	N/A
Cockpit capsule	1825 pounds	3975 pounds
Fuselage capsule	7025 pounds	2575 pounds

Table II. Weight penalties of escape systems.

the four escape systems and the aircraft weight gain for the cockpit and fuselage capsules. The penalties for the encapsulated seats and cockpit capsule included additional cockpit space to stow and provide clearance for encapsulation elements. Any additional space translated to more structure, hence more weight. Preliminary tests showed that capsules tumbled at high rates, requiring complicated and heavy stabilization systems; these requirements drove capsule weights higher. [Ref. 11]

The designers calculated that each 500 pounds of weight gain would penalize performance by 100 miles per hour. They viewed drag and weight as "costs" coming directly out of their pockets. Any proposed weight gain was therefore thoroughly reviewed. Table III presents the weight and speed penalties of the cockpit and fuselage capsules. A performance penalty of up to an entire Mach number would have resulted from use of a cockpit or fuselage capsule. [Ref. 11]

	Weight Penalty, pounds	Airspeed Penalty, MPH	Mach Penalty (at 160,000 feet)
Cockpit capsule	3975	795	1.06
Fuselage capsule	2575	515	0.68

Table III. Performance penalties of capsule ejection systems.

Program requirements eventually drove the selection of an escape system as much as engineering design. The development of a fuselage capsule was estimated to be as large a technical challenge as the rest of the air vehicle. The ejection seat required 50% less development time than a capsule would have. Even at that, 7000 man-hours were consumed in the design of the escape system. [Refs. 11 and 12]

Powerful arguments were made for sophisticated capsules, as the result of accidents which had occurred. George Smith, a North American Aviation test pilot, had recently ejected from an F-100 while supersonic, 647 knots at 6000 feet. While Smith was the first

survivor of a supersonic ejection, he suffered horrific injuries due to the high dynamic pressure wind blast. Consequently, Smith spent the next year in hospital being reconstructed.

The other tragedy to cast a pall on the entire research airplane program occurred when Captain Mel Apt died in an X-2 escape capsule. The X-2 escape capsule was designed to separate from the airframe upon pilot initiation, and decelerate with a parachute. The capsule was not a touchdown vehicle. The pilot was to jettison the canopy and bail out of the capsule after the deceleration parachute had deployed. Many of the test pilots were highly critical of the X-2 escape system design for its over-reliance on a conscious pilot, particularly after Chuck Yeager's X-1A incident. The X-1A, which lacked an ejection seat, departed controlled flight after rocket cut at Mach 2.5 and 76,000 feet. The aircraft plummeted over 50,000 feet before recovery; the buffeting was so severe that Yeager broke the canopy with his head, and was rendered briefly unconscious. Yeager reported that he would have gladly used an ejection seat, had it been available. [Ref. 13]

On 7 September 1956, Capt. Apt had flown a nearly perfect acceleration profile, taking the X-2 to a new record of Mach 3.3 at 70,000 feet. The X-2's directional stability decreased with increasing supersonic airspeed. A roll to yaw coupled oscillatory divergence occurred with such violence that Apt was knocked unconscious after initiating capsule ejection. He was not able to bail out of the capsule. [Ref. 13]

In light of the aforementioned accidents, the Air Force issued a policy requiring ejection capsules for all USAF airplanes. The capsules were to be automatic sequencing types with parachutes to carry the capsule with pilot inside to touchdown. The X-15 was being designed at the time of the policy release and was initially included. The need to prove an effective supersonic ejection seat in order to gain waiver approval was a major hurdle. [Ref. 12]

The North American Aviation ejection seat as finally designed, demonstrated and installed is shown in Figure 24. The critical elements for a survivable supersonic ejection

were the stabilizing wings, telescoping stabilizer booms, and the pressure suit. The stabilizers allowed the seat to separate from the airframe without tumbling, while decelerating. The pressure suit and full face helmet provided wind blast protection.

Figure 24. After Ref. [11].

With respect to the design of the ejection seat, North American Aviation's test pilot, Scott Crossfield, made some interesting design decisions. Crossfield was unwilling to accept padding on the ejection seat as it weighed two pounds. He calculated an eventual weight penalty of 7 - 14 pounds for the padding. He did recognize that given the mission profile time from strap in, B-52 start, climb and cruise to drop position, several hours would expire before the 10 minutes of X-15 flight time. Even the most iron bottomed test

pilot would become fatigued. Crossfield decided to consult with the industrial manufacturing organization most familiar with designing metal seats for long seated periods in conditions of hot, cold, and vibration. He selected International Harvester to help design the metal seat pan, based on their knowledge of human kinematics and experience in shaping metal seats for agricultural and heavy equipment. The seat pan for the X-15 was thus largely a copy of an International Harvester tractor seat. Crossfield wrote that the seat pan designed was the "minimum weight and maximum comfort, and will keep the pilot solidly in place in the event of rough flight." [Ref. 12]

The MC-2 pressure suit was a breakthrough and a significant success designed and manufactured by the David Clarke Co. Clarke developed what was then a new linked mesh type pressure equalizing garment to be worn under the shiny aluminized "space suit'. This allowed for the first time adequate flexibility and range of movement in the cockpit. Previous attempts had been cumbersome, restrictive affairs, resembling hard hat divers rigs. Pressurization loads had been borne by the suit skin, and limb mobility was severely restricted when the whole outfit went as rigid as an inflated surgical glove. The incorporation of complicated accordion-like pleated bellows joints to permit limb articulation had not been a fully satisfactory solution. The MC-2 was the first practical pressure suit for extreme high altitude and space flight. To reduce the chance of fire and explosion in the cockpit, the suit was pressurized with inert nitrogen. A rubber dam around the neck prevented mixing of the nitrogen with the 100% oxygen environment in the helmet. The cockpit was itself filled with nitrogen. The Clarke MC-2 pressure suit was so successful that while developed strictly for the X-15 project, it was adopted for the Mercury and Gemini projects, setting the standard for future pressure suits. [Refs. 8 and 12]

D. FLIGHT CONTROL SYSTEM

1. General

One of the challenges facing Feltz and the X-15 design team was the need for two sets of control, one for atmospheric flight and the other for exo-atmospheric space-equivalent flight. Experience with flight research vehicles had shown that some of the dangerous flight regimes were those involving transition from one mode of control to another. The separation and blending of aerodynamic and reaction controllers posed another hurdle to overcome.

2. Cockpit Control Stick System

The complexity of the control stick system began with the RFP requirement for a center and sidearm controller as well as a separate control stick for a reaction control system. The X-15 cockpit with the three control sticks is shown in Figure 25. As

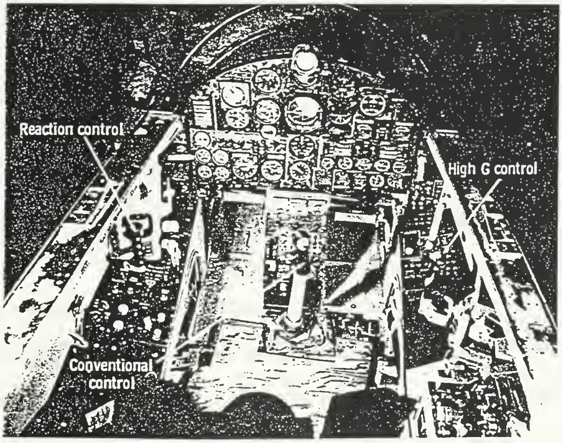
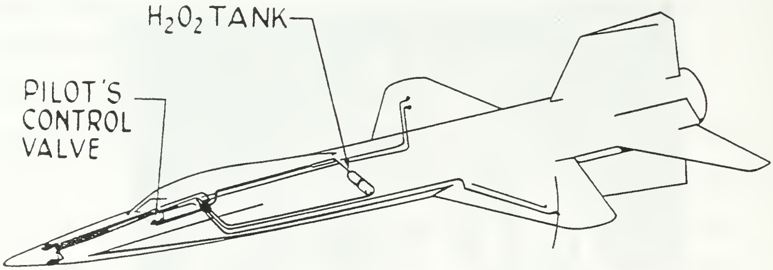


Figure 25. X-15 Cockpit and Control Sticks. From Ref. [8].

illustrated, the control stick arrangement featured a conventional center stick, a sidearm controller on the right side of the cockpit and another side stick controller on the left. The center stick was for atmospheric control via the control surfaces and was mechanically interconnected to the right sidearm controller. The right sidearm controller was for precise control of the flight path under conditions of high g forces during rocket propelled acceleration and later in re-entry. The left side controller was for operation of the reaction control system used in space-equivalent flight. [Ref. 8]

3. Reaction Control System

The X-15 was the first airplane to use reaction control rockets for attitude control in the high altitude, space-equivalent flight phase. The reaction control system was manufactured by Bell Aircraft Corporation, and is presented in Figure 26. The thrust for



EACH SYSTEM	ACCELERATION	THRUST
PITCH	2½°/SEC^2	113 LB
YAW	2½°/SEC^2	113 LB
ROLL	5°/SEC^2	50 LB

Figure 26. Reaction Control System of X-15. From Ref. [9].

attitude control was generated by steam. The pilot's left control stick activated valves to release hydrogen peroxide from the amidships storage tank. The hydrogen peroxide flowed over a catalyst bed of silver and stainless steel screens, which produced superheated steam. The steam exited through four nozzles in the nose for roll, pitch and yaw control and nozzles on each wing for roll control. The reaction control system was used for setting the re-entry attitude which was critical for controlling aerodynamic heating. The reaction controller could not change the flight path of the X-15, but only the attitude during ballistic flight. [Ref. 13]

4. Aerodynamic Flight Controls

The wings were of a modified 66005 airfoil section with a mere 5% thickness ratio [Ref. 14]. They could not support extensive actuators or flight controls, and only incorporated flaps. Even the main landing gear was located in the extreme aft fuselage, alongside the ventral stabilizer. The wing design precluded conventional ailerons; the X-15 used a unique rolling tail. The X-15 and F-107 (a North American Aviation interceptor prototype) were the first aircraft to use a stabilator which moved the two panels opposite to each other for roll control and in the same direction for pitch control. [Ref. 8]

The vertical and ventral stabilizers were also unique for the high speed research aircraft. Previous experience with other aircraft at high Mach numbers and angle of attack had revealed blanking of the vertical stabilizer, which is usually located above the fuselage This led to loss of directional stability and loss of yaw damping. The X-15 incorporated a ventral stabilizer beneath the fuselage almost equal in area to the vertical stabilizer and is shown in Figure 14.a. When at positive angles of attack, the ventral stabilizer would be operating clear of the disturbed flow of trailing shock waves. The size of the ventral stabilizer was enough to cause it protrude beyond any reasonable landing gear length. The solution was to jettison a major portion of the ventral stabilizer prior to landing after having decelerated to below supersonic speeds. The jettisoned surface would descend on its own parachute, and be recovered. The loss of the ventral stabilizer would of course reduce

directional stability. Partly to offset this loss, speed brakes which could be used throughout the entire airspeed and altitude range were incorporated at the base of the vertical stabilizer. This could restore a measure of the directional stability, albeit at the penalty of a drag increase. [Ref. 8]

5. Hydraulic Boost

The rolling tail with large control surfaces operated in a high dynamic pressure range which caused high actuation forces. A hydraulic system was necessary to permit control movement. The inclusion of a hydraulic system also permitted much easier insertion of automatic flight control system (AFCS) inputs. The hydraulic actuator was commanded to move by the AFCS, with the movement being downstream of the pilot's input. Due to the criticality of the hydraulic system, a fail-safe design was required. A general schematic of the aerodynamic control system and the hydraulic boost is presented in Figure 27.

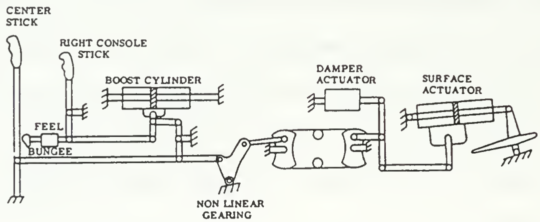


Figure 27. Aerodynamic Control System Schematic. From Ref. [15].

6. AFCS Development

Development of a satisfactory automatic flight control system (AFCS) for the X-15 was vital to the success of the airplane. The AFCS design was dependent on simulator modeling of the airplane dynamics and pilot inputs. The simulation program included over

400 simulated re-entries "flown" in the Navy centrifuge at Johnsville, Pennsylvania which indicated that pilot control is possible to 12 - 15 g's. This was one of the first uses of simulators in a feedback loop for development of control laws and design of an AFCS. "Classical analysis did not predict an instability which without electronic assistance, the X-15 would be uncontrollable over a large part of the anticipated flight envelope." Through the incorporation of an effective AFCS which capitalized upon the strengths of a pilot: "...automatic control came to be looked upon not as a replacement for the pilot but as a useful, helpful, even necessary aid, without which the full potential of the X-15 would not have been achieved." The X-15 and the F-107 were the first airplanes to employ an irreversible flight control system with artificial feel and stability augmentation. [Ref. 8]

Simulator analysis of AFCS designs required a mathematical model of the total aircraft, including the pilot. While the static force and displacement characteristics of pilots manipulating aircraft controls had been well documented, the dynamic response of the human operator was not well understood. Empirical methods were used to develop mathematical models of aerodynamic parameters in response to pilot input. "Some of the control system and physical [aircraft] characteristics were tailored to [the project pilot's individual] capabilities to attain the desired airplane-pilot combinations." Still, no flying qualities criteria had been developed for hypersonic flight at angles of attack greater than 10° or for the space-equivalent region. Thus high AOA flight was still an area for careful exploration. [Ref. 8]

The ventral stabilizer produced an adverse rolling moment due to yaw or sideslip. The adverse rolling moment generated a positive dihedral effect which caused the sideslip to increase further which itself would cause the roll to increase further. This severe yaw to roll coupling complicated the stability and control, while inadequate roll damping was another difficulty. The horizontal and vertical stabilizers produced stability in pitch and yaw. However, no purely aerodynamic means of achieving roll stability was available. As the airspeed and altitude increase, aerodynamic damping forces decrease. Thus, the X-15

required a powerful roll damper. Previous roll dampers had limited authority, only a few percent of the pilots' authority. The X-15 roll damper had "twice the roll-control capability of the pilot." [Ref. 8]

The incorporation of hydraulically powered controls provided a means for the introduction of AFCS inputs. It also greatly increased the flight control system complexity. This ran in opposition to the desire to preserve simplicity and keep weight down. Eventually, the designers found that by accepting the weight and complexity of a sophisticated AFCS, the airplane could be flown to a greatly expanded envelope of airspeed, altitude and control. It was however dependent on the absolute functional reliability of that AFCS, for without it's assistance the pilot might not have been able to safely control the airplane. This drove the designers to incorporate a fail-safe AFCS architecture and redundant systems. By making the aircrew centered design decision to accept the complexity, redundancy, and weight of a sophisticated AFCS to assist the pilot, the altitude capability of the aircraft was increased by over 40% from 250,000 feet to 354,200 feet. [Ref. 8]

The degree of precise control afforded by an AFCS was also vital during the powered flight phase. In those first 85 seconds, the entire path of the 10 -12 minute flight was determined. Each flight followed a common, pre-computed climb profile to a point where the pilot either pushed over to accelerate for a high Mach run or continued climb for a high altitude flight. During the early phases of the program, the response of the X-15 to the reaction controller was undamped as shown in Figure 28, resulting in over control and PIO. The original AFCS was modified to provide artificial damping during reaction jet controlled flight. Without this, the expanded altitude envelope would likely not have been attainable. [Ref. 8]

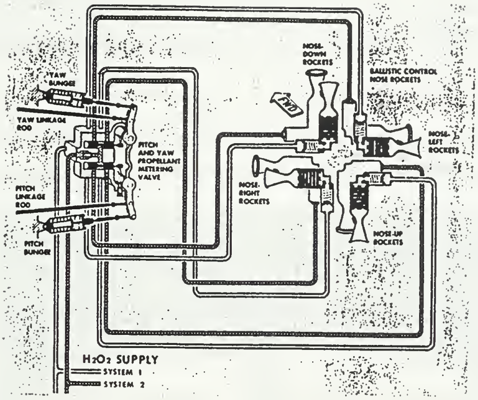


Figure 28. Reaction Control Schematic, Before Rate Damping. From Ref. [15].

7. Self-Adaptive Controller

The X-15 had a tremendously wide range of airspeeds, altitudes, dynamic pressures and several different control modes. In response to these factors, the X-15 control effectiveness was widely variable, causing a difficulty in piloting. The X-15 was used as a research platform to develop a self-adaptive controller designed and built by Honeywell. This controller integrated aerodynamic and reaction controllers by use of a gain changer. The gain changer adjusted control system gain to provide a desired dynamic rate response for a given stick input throughout the entire flight regime. Rate gyro feedback provided for stability augmentation in pitch, roll, and yaw. [Ref. 8]

The self-adaptive controller was another element crucial to expansion of the altitude envelope. The original controller allowed re-entries from up to 250,000 feet; the adaptive controller and a revised vertical stabilizer allowed re-entries from the higher altitudes

achieved later. One of the significant advantages of the self-adaptive controller was that it allowed increasing the angle of attack (AOA) capability of the X-15. A limiting factor for re-entry from higher altitudes was the increase in angle of attack required to prevent excess airspeed and heating rates. The X-15 was initially considered to be limited to an AOA range of up to 10°. With the adaptive controller, the AOA range was tripled to 30°. [Ref. 8]

E. DISPLAYS

The quality of pilot's displays proved to be critical for mission success with the X-15. NASA reported: "The pilots accomplish the major phase of every flight solely by reference to cockpit instruments. Thus the instruments are no less important than the control system". [Ref. 8]

Joseph Walker was the NASA Chief Aeronautical Research Pilot at the NASA Flight Research Center and one of the principal pilots of the X-15 project. In a paper to the Society of Experimental Test Pilots, Walker presented criterion for instrument presentation. These criterion included:

1. "[The] pilot *is* capable of accomplishing the intended mission if he is designed into the control loop."
2. "The prime presentation should be at the center of focal interest."
3. The design should retain sufficient direct external field of view such that a visual landing could be performed.

Walker was later to tragically die when participating in a General Electric publicity photo shoot of a formation of General Electric engine powered jets. His F-104 was caught in the swirling wingtip vortices from the XB -70 Valkyrie, which was the lead plane of the formation. Walker's Starfighter was swept up over the Valkyrie's right wing tip and spanwise across the delta wing trailing edge, shearing off the XB-70's vertical stabilizers. The F-104 cartwheeled and exploded. The Valkyrie flew briefly before departing

controlled flight. The XB-70 crew attempted to eject; the encapsulated ejection seats failed to program correctly. All souls aboard were lost.

Figure 29 illustrates the field of view from the X-15 pilot's design eye point and also the instrument panel. While the field of view is certainly not generous enough for the air combat maneuvering mission, it was adequate for landings. The X-15 required two different reference sources to provide position and rate data to display for the pilot. The pitot and static source instrumentation were only usable during atmospheric flight, and

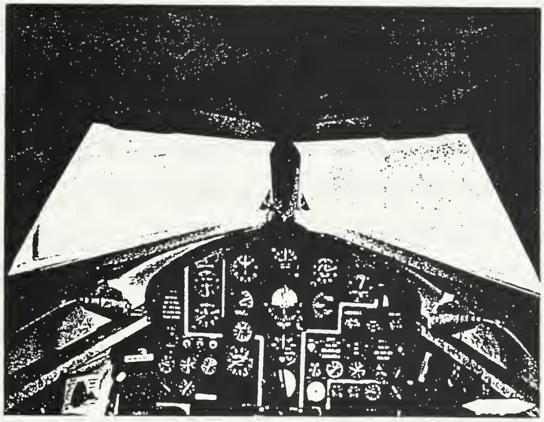


Figure 29. Pilot's View of X-15 Canopy and Instruments. From Ref. [15].

were used for launch and landing. The pressure referenced airspeed indicator and altimeter are to the left of the attitude/direction indicator (ADI). The three instruments to the right of the ADI are altimeter, velocity, and rate of climb/descent and are driven by an inertial navigation unit for use in the space-equivalent region. The B-52 mothership provided alignment, stabilization, and continuous updates to the inertial system until the X-15 was dropped for rocket motor ignition. After launch, the inertial platform operated in a dead reckoning mode. [Ref. 15]

Tests conducted with the X-15 simulator and the Navy's centrifuge facility determined which flight parameters were most important to the pilot. The two most critical parameters were angle of attack and sideslip. The challenge in this case was to obtain the alpha and beta values in the very low dynamic pressure, space - equivalent region where conventional AOA and sideslip sensors would not work. The system would also have to withstand temperatures of up to 2500° F. The solution developed was the NASA Q ball, a 6 1/2 inch diameter sphere mounted at the apex of the nose. It was a hot nose flow direction sensor (similar in concept to a hot wire anemometry sensor), and was servo driven for alignment with the flow. It proved to be highly successful for precise control of the X-15. [Ref. 8]

Angle of attack and sideslip parameters had to be provided to the pilot in a usable form. The ADI shown in Figure 29 had vertical and horizontal pointers. The pointers were center nulled to indicate zero sideslip and zero angle of attack and thus were command deviation indicators (CDI). The vertical pointer moved left to right to indicate the direction and magnitude of sideslip. The horizontal pointer moved up and down the ADI to similarly indicate angle of attack. Walker noted that the presentation of the most critical parameters must be of a large enough scale to detect small errors, and have well damped indicators. The earlier ADI was a much smaller diameter, less sensitive instrument on which detection of error was difficult, hence the change to the 5 inch diameter ADI shown in Figure 29. [Ref. 16]

F. COCKPIT DESIGN NOTES

The landing gear system had no position indicator lights to confirm up or down status. Crossfield states that the decision to eliminate the sensors, indicators, and wiring saved approximately five pounds in direct weight, which could translate to an aircraft weight savings of 17 - 35 pounds. The chase aircraft could call the landing gear position. The X-15 was landed at well over 200 miles per hour with glide descent rates in excess of 30,000 feet per minute. It did not need the additional drag of the landing gear for energy

management as other research airplanes did. Extension of the landing gear was delayed to avoid an even higher descent rate. Crossfield felt the position indicators were not necessary, since the landing gear was up till the last moment before touchdown. If the landing gear did not extend, there was of course, no engine for a go-around. He felt that the gear position indicators just did not matter, as the pilot was committed to land. [Ref. 12]

A major subsystem of the X-15 was the air conditioning unit to protect the pilot and instrumentation. In the temperature regime which the X-15 operated, this system was of vital aircrew centered design importance as the aircraft structure was to heat to 1200°F. The working fluid in the heat exchanger was liquid nitrogen which cooled the gaseous nitrogen filling the cockpit. [Ref. 8]

The X-15 was mounted to the B-52 wing as shown in Figure 30. The carriage of the X-15 under the wing was dictated by ground clearance requirements. The X-15 protruded too far from the bomb bay to permit belly carriage, which was the practice with earlier aircraft. The mount had to be designed such that the cockpit of the X-15 was clear of the wing to permit an ejection while being carried. This was the only emergency escape possible for the X-15 pilot. Previous belly carried aircraft such as the X-1 and X-2 permitted egress to the mother airplane, as in the case of Joe Walker and the X-1A. In this incident the rocket fuel system exploded; the mother ship crew acted with extraordinary bravery to rescue Walker, and the X-1A was jettisoned. An X-1D was also jettisoned after a fuel explosion. The first X-2 delivered also suffered a fuel explosion and was jettisoned as well, falling into Lake Ontario. Bell test pilot Skip Ziegler was killed in the accident. In previous aircraft, the pilot could man the research airplane just before drop, avoiding being fatigued by several hours in a cramped cockpit. The underwing carriage of the X-15 caused the pilot to be out on the wing from well before B-52 engine start; three or more hours might pass before the X-15 was launched. In the case of the X-15, the tradeoff

between crew comfort and fatigue was offset by the ability to eject while on the wing or after jettison by the mother ship. [Ref. 11 and 13]

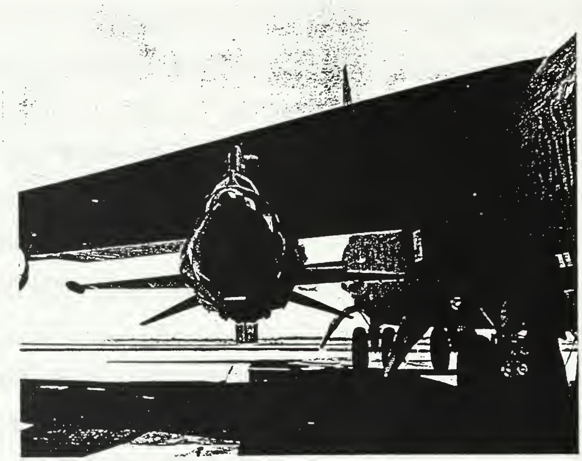


Figure 30. X-15 Mated to B-52 Wing. From Ref. [8].

G. X-15 IN SERVICE

1. Ventral Fin and Rudder

The ventral rudder below the ventral stabilizer was found to actually add to hypersonic roll instability. The X-15 was found to be too sensitive to rudder inputs in the hypersonic regime. Removal of the ventral rudder, the portion which was jettisoned before landing, leaving only the ventral stabilizer, did reduce the directional stability but greatly increased controllability. On the 42nd flight, the X-15 was flown without the ventral rudder to test the theory. The results were satisfactory, and from flight number 70 on, no ventral rudder was carried. The removal of the ventral rudder also allowed the carriage of a dummy ramjet later in the program. [Ref. 9]

2. X-15A-2

The second X-15 was involved in two accidents, neither fatal. The first was on the third flight for the airplane, fourth for the program. The engine did not light, and NAA test pilot Scott Crossfield could not jettison the fuel quickly enough before landing. After the main landing gear touched down, the additional weight caused a higher than normal nose down moment at nose gear touchdown. The fuselage broke aft of the cockpit. Crossfield was fortunately not seriously injured and the airplane flew three months later.

The second accident was more serious. The airplane is shown in Figure 31. John McKay was the pilot for the 74th flight of the program. The flaps would not extend and consequently the touchdown speed of 290 miles per hour was well above the normal of 200 miles per hour. The left main skid failed due to the aerodynamic downloads on the horzontal stabilizers. The airplane swerved broadside and rolled. McKay suffered three crushed vertebrae. He recovered in six months to fly the X-15 again, although he was now 3/4 inch shorter.

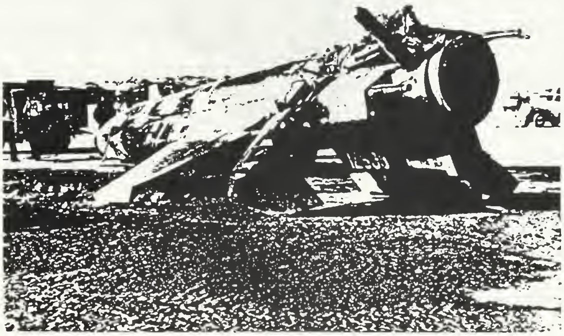


Figure 31. Number Two X-15 Landing Accident. From Ref. [8].

The airplane was rebuilt to the considerably modified X-15A-2 configuration shown in Figure 32. The most visually striking change was the drop tanks. The drop tanks along with a lengthening plug in the fuselage permitted 13500 pounds more propellant and oxidizer to be carried. This enabled a longer engine run time and thus higher speeds to be attained. The drop tanks were jettisoned while passing Mach 2. [Ref. 8]

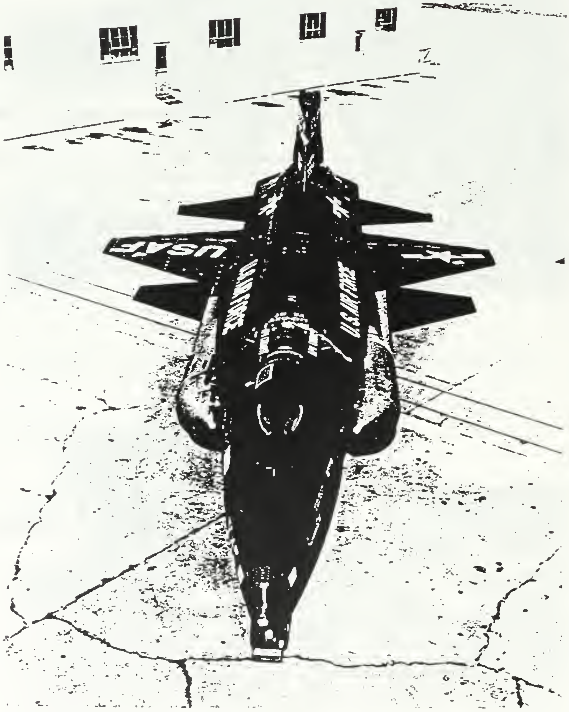


Figure 32. X-15A-2 Final Configuration. From Ref. [8].

One of the aircrew centered system design changes were the elliptical windshields. The original rectangular windshields had shattered on several occasions due to thermal stresses experienced at high aerodynamic heating levels. The elliptical windshields avoided the stress risers of corners.

One of the other changes, less visible was the coating of temperature sensitive areas with an ablative material. This was to protect the structure by sacrificing the ablative coating which absorbed and conducted heat away as it sloughed off. The ablative covering on the nose redeposited on the windshields. The pilots insisted that they really needed the forward view for landing. This drove another aircrew centered design change. An "eyebrow" was installed over the right windshield. The eyebrow was closed during most of the flight. The left windshield and eyelid would get covered with the ablative deposits during the high speed flight phase. The flight parameters were not external visual during this time, rather the pilot was flying with reference to the inertial instruments. The eyelid was retracted to allow the pilot visual reference during landing.

The drop tanks were intended to allow the X-15 to fly at up to Mach 8. The highest speed attained was Mach 6.7 with Pete Knight at the controls and a dummy ramjet on the ventral fin. In a NASA retrospective, this was termed the limits of ablative protection due to "near-destructive heating effects due to poor understanding - and consequent prediction - of heating interactions and the ability of an experimental ablative coatings to cope with the added stresses of a near Mach 7 thermal environment." This airplane never flew again. [Ref. 9]

3. Aircraft Number Three Accident

The X-15 program was marred by a tragic fatal accident. The number three airplane was being flown by Michael Adams on 15 November 1967. This was the 67th flight for the airplane and the 191st flight of the X-15 program. Dr. Richard Hallion, Air Force Flight Test Center historian, cited the following factors in this accident: "a combination of a physiological predisposition to vertigo, distraction, and some control system degradation

from an electrical disturbance, and a total control system failure triggering a limit-cycle oscillation of the Honeywell adaptive flight control system, led to the loss of the X-15 No. 3 and pilot Mike Adams...Contributing to the accident were inadequacies in the amount and type of information available to the ground controllers. These deficiencies were subsequently corrected." [Ref. 9]

4. Last Flight

Only eight more flights were conducted in the X-15 program. The last flight was on 24 October 1968 with X-15 number one. Bill Dana was the pilot; a speed of Mach 5.38 and an altitude of 255,000 feet was attained. [Ref. 9]

H. FOCUS ON AIRCREW CENTERED DESIGN ASPECTS

Hypersonic research and increasing the knowledge of space systems operations were the reasons for the existence of the X-15. Several significant aircrew centered design decisions directly determined the success of the X-15 program. The foremost was the inclusion of a pilot. The pilot proved to be necessary for the success of the X-15 as an airplane and a research tool. Aircrew centered system design was significant in the following areas:

1. Pilot presence made the AFCS design simpler, which led to greater reliability and reduced weight.
2. The pilot was necessary as the data gatherer, he was the principal payload yet was only 0.86% of the launch gross weight.
3. Clarke MC-2, the first successful pressure suit, was designed and built for the X-15, and was so successful that it was used for the space program.
4. Supersonic escape system
    - ejection envelope determined by probability analysis
    - lightest system which covered the desired escape envelope was selected, avoiding the loss of a full Mach number with the heavier, more sophisticated systems

• first ejection system designed for supersonic envelope; demonstrated supersonic ejection at high dynamic pressure from test sled.

5. Hydraulics permitted the pilot to overcome actuation loads and provided for the incorporation of the first irreversible flight control system with artificial feel and stability augmentation.
6. The pilot actuated reaction control system proved feasibility of attitude control in space-equivalent region. It was a forerunner of reaction controllers in space programs.
7. While the AFCS increased complexity and weight, it allowed the pilot to expand the aircraft's envelope. In particular;
    - self-adaptive controller increased the angle of attack range by 300% and
    - enhanced high altitude controllability such that the maximum altitude was increased by 40%
    - AFCS rate damping was incorporated into the reaction control system, which permitted fine control of attitude at high altitude.
8. Pilot displays were as crucial to the X-15 mission as any other onboard system. The following were lessons learned or demonstrated;
    - large display should be used for the parameter of greatest interest
    - damped state and quickened command cues permitted the pilot to set the attitude required for the flight phase
    - adequate displays and AFCS enable the pilot to manually fly atmospheric departure and re-entry profiles.

The X-15 project was born in December 1954, with the first glide flight in June 1959. The three aircraft flew 199 research missions to an altitude of greater 354,000 feet, to a speed greater than 4520 miles per hour or Mach 6.7. Theodore Ayers, deputy director of NASA Dryden said of the program: "The X-15 program has been recognized as one of the most productive and successful activities in aeronautical flight research. Approximately

800 technical research reports were produced." This was equivalent to "the full-time research effort a 4000 person Federal research center working for 2 years." [Ref. 9]

Another NASA report on the X-15 program commented on the inclusion of pilots in the concept: "Now, 120 flights have shown us that this traditional concept for piloted flight research, while needing some modification is also applicable to the space era. Many now wish that all the X-15 components would exhibit the same steady component reliability that the pilots do." [Ref. 8]

V. F-16 FIGHTING FALCON

A. BACKGROUND

1. Fighter Combat Analyzed

The F-16 has proven to be a highly successful fighter airplane in worldwide service. The design had its roots however, in dissatisfaction with 1960s era fighters, particularly the F-4 Phantom conducting aerial combat in Southeast Asia. The shortcomings of these airplanes, particularly from an aircrew centered philosophy were manifold. The original design concepts severely limited the ability of US pilots and aircrew to effectively operate the fighters against relatively simple, lower performance airplanes such as the MiG-17 in the combat environment of Vietnam. The exchange ratios for the US Air Force in Vietnam were as low as 2 to 1. Contrast this with the Korean conflict exchange ratio of 14 to 1 after the introduction of the F-86. The Sabre was considered to be the last of the "dogfighter's airplane" (i.e., simple, lightweight, and maneuverable) till the introduction of the F-16.

As a result of the Southeast Asia experience, a group of military and civilian defense officials examined the combat data with a pilot's knowledge of the mission, to determine what qualities a pilot would need from a fighter airplane to survive and prevail. The group became known as the "Fighter Mafia" and included a former fighter instructor, Major (later Colonel) John Boyd and defense analyst Pierre Sprey, who was working for the assistant Secretary of Defense for Systems Analysis. The results of their analysis began to circulate the Pentagon in 1970. Much of the analysis refuted the concept that a few fighters of sufficient quality could rule the skies against hordes of less sophisticated airplanes. These results were particularly interesting to others in light of the tremendous cost overruns in the F-111, F-15, and F-14 programs. The F-14 case was highly unique in that only a financial bail out in the form of loans from an Iranian bank kept the program afloat. [Ref. 17]

2. Fighter Aircraft Design Priorities

The "Fighter Mafia" identified four priorities for the design of an air to air combat airplane. The priorities were driven by the pilot's need for situational awareness while not being restricted by the limitations of the aircraft or current technology; in short they were aircrew centered.

The first priority identified was to achieve surprise without being surprised. Analysis of fighter versus fighter data from WW I through Vietnam indicated that 65 - 85% of all kills were unaware of the attacker. Offensively, this priority dictated an excellent field of view to increase likelihood of visual acquisition of opponent, and a cruise speed higher than the opponent's in order to close to within weapons range. To defend the fighter, small size and smokeless engines to reduce the aircraft's own visual signature and sparing use of radar to avoid an electronic signature were needed. [Ref. 17]

The second priority was to overwhelm the enemy by sheer numbers, not necessarily in the dogfight but over a wide area, even to theater level over a sustained period of time with a high sortie rate. A solution was to employ many simple fighters rather than a few sophisticated interceptors. A high sortie rate was possible with simplicity of design (e.g., fewer failure modes) given that good maintainability was designed into the airplane. [Ref. 17]

The third priority was to outmaneuver the enemy when in close combat. Maneuverability required high acceleration, high climb rate, and high turn rate which arise from aggressive roll and pitch rates with sustained high g loads. A high thrust to weight ratio from the smallest airframe wrapped around the most powerful engine would yield the desired aircraft climb, turn, and acceleration performance, quantified by excess specific thrust (P_S). Also necessary was the ability to outlast the enemy in a combat engagement. The other requirements conflict with each other in wing design, requiring compromise, primarily in the wing planform and aspect ratio. For example, a high aspect ratio is desired

for sustained turn, while low aspect ratio is desired for roll rate and roll acceleration. Sufficient fuel is needed to outlast the enemy, and could be achieved with an internal fuel fraction target of approximately 0.3 of clean takeoff weight. [Ref. 17]

The fourth priority was to give the pilot the ability to use split second firing opportunities. The Phantom had three severe limitations during an in-close dogfight. First, the early missiles required a "settling time" between target acquisition and launch. Second, the missiles could not be launched at g loads greater than 2.5, severely limiting their usefulness in close combat. The early Sparrow and Sidewinder missiles had been designed for use against non-maneuvering targets, particularly bombers. Air Force records indicated that the kill probability (P_k) for these two missiles as used in Vietnam dropped from 80% to a range of 8 - 15% [Ref. 19]. Third, the Phantom lacked a gun, which could have made up for the two other limitations during a dogfight. [Ref. 17]

The Phantom had been designed as a fleet defense interceptor to use long range missiles in protecting the carrier battle group, in an era when the gun was viewed as outmoded. Contemporary combat data indicated the contrary. During the Six Day War, the Israeli Air Force scored 50 kills, all with guns, despite having missiles available and in fact using some missiles. The USAF Southeast Asia records also supported the utility of guns. The F-105, armed with a 20 mm cannon and Sidewinders, scored 25 of 27 kills with guns (93%). The F-4C and F-4D with a pod mounted 20 mm cannon (which was viewed as being inaccurate and taking up a weapons station) scored 10 of their 86 kills. The F-4E scored 16 of 107 kills with it's internal 20 mm cannon. The B-52 even had 2 kills credited, made with .50 calibre machine guns. [Ref. 19]

The proposed solution to the fourth priority given the aforementioned limitations and the Vietnam data was to emphasize simplicity: guns for short range and Sidewinders for longer range. Multiple engagements with adequate munitions, and minimizing the time between opportunity and attack are the key points to succeed against an aggressively maneuvering opponent. [Ref. 17]

Boyd and Sprey were influential in pressing their analysis and their identified priorities into later Air Force fighter programs. Boyd's work to develop the concept definition for the Fighter Experimental (FX) program became the F-15, and the Advanced Day Fighter became the Lightweight Fighter program.

B. LIGHTWEIGHT FIGHTER PROGRAM

The Boyd/Sprey priorities were eventually incorporated into a Request For Proposal (RFP) for a Lightweight Fighter (LWF) released in January 1972, under the competitive prototyping concept of Deputy Defense Secretary David A. Packard. The RFP minimized strict performance targets and specifications, and did not constrain the designers to the existing USAF force structure. This allowed the designers greater freedom in the airplane design process and in the concept of employment. The airplane called for in the RFP was to be developed as a technology demonstrator with materials and technology either on hand or available in the near term: no technological breakthroughs were sought. Thus, the prototypes would bear the "Y" prefix denoting developmental airplane instead of the more usual "X" for experimental. The airplanes were to be built under a cost plus fixed fee type of contract. [Ref. 18]

In the RFP, the Air Force did call for three broad objectives. The airplane was to investigate and capitalize on emerging technologies, it should reduce the risk involved in full scale development and follow on production, and it should present a choice of technological options to military needs. [Ref. 18]

Instead of trying to counter a specific threat aircraft, the USAF called for the LWF to be designed to conduct aerial combat in a band of conditions from 30,000 to 40,000 feet at speeds of Mach 0.6 to 1.6. The range of flight conditions emphasized turn rate, acceleration and range to permit intercept and engagement of a variety of Warsaw Pact aircraft in service and development. [Ref. 18]

Somewhat predictably, the five proposals received were largely refinements of existing aircraft or projects. Lockheed presented the CL-1200 Lancer, essentially a revamped F-104 Starfighter. Ling Temco Vought proposed it's V-1100, based upon the Crusader and Corsair II models. Northrop entered two variants on a similar theme: the single engined P.610 and twin engined P.600, which dated to 1966 as a low cost F-5 replacement proposal to the Dutch. General Dynamics proposed their Model 401, which they had started work on in 1968. From the field of candidates, the Air Force selected the Northrop P.610 and the General Dynamics Model 401 for development. Two prototypes of each were to be built for a fly-off competition. [Ref. 17]

C. YF-16

1. General Design

The General Dynamics proposal, the YF-16 is illustrated in Figures 33 and 34. General Dynamics did not attempt to push individual technologies to a "cutting edge" in designing their fighter. The overall aircraft was designed for component and detail assemblies to have high commonality, standardization and low cost materials wherever possible. [Ref. 18]

It was only in achieving performance goals that high leverage new technologies were employed. Some of those technologies were: relaxed static stability, a fly-by-wire flight control system, wing-body blending as had been done on the Saab Draken, variable wing camber through an articulating leading edge and maneuvering flaps, and the design of the pilot's station. [Ref. 18]

Overall, the YF-16 was designed to be a highly maneuverable, low cost single place fighter. The primary design goal was to achieve high maneuverability through low wing loading and high thrust to weight ratio. The Pratt and Whitney F100 engine allowed a thrust to weight ratio greater than one.

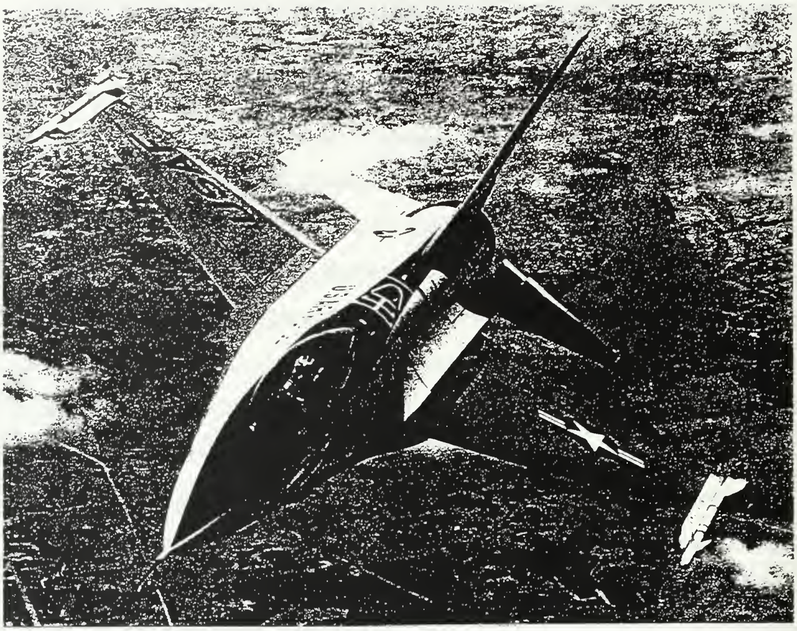


Figure 33. General Dynamics YF-16. From Ref. [17].

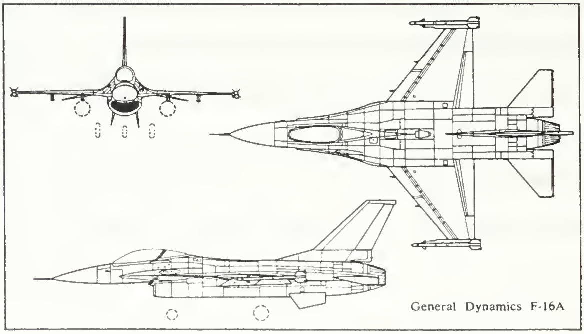


Figure 34. F-16 General Arrangement. From Ref. [20].

2. Fighter Design Priorities as Realized in the YF-16

a. Cockpit

The YF-16 embraced the four aircrew centered priorities of the "Fighter Mafia". The most striking aspect of the YF-16 was the cockpit design and the field of view (FOV) afforded by the bubble canopy. While the generous bubble canopy certainly imposed a supersonic drag penalty because of the loss of fineness ratio, the ability to visually scan in all directions was judged to be more worthwhile. The canopy dispensed with the traditional forward windscreen bow, and instead was a one piece transparency hinged at the aft end for cockpit access. The only canopy reinforcing bow was well aft. The canopy provided a full 360° field of view in the horizontal plane and 15° downward vision over the nose. The cockpit sides were contoured to permit a sideward 40° down vision. The pilot's field of view and a total vision plot are presented in Figure 35. [Ref. 17]

The one piece bubble canopy had no fixed windshield to protect the pilot from wind blast in the event of canopy loss. Retention of the canopy was thus of great concern. The solution was eight locking latches to secure the canopy, of which six are visible to the pilot. The HUD was also designed to act as a windshield should the canopy be jettisoned or lost. [Ref. 22]

Inside the canopy, the cockpit also demonstrated some radical thinking. The pilot's seat was raked back to a 30° angle with a somewhat raised heel rest line. The conventional fighters of the period had seats inclined at only 13°. General Dynamics (GD) engineer, Jack Buckner indicated that GD felt that the 30° ejection seat tilt increased the pilot's g tolerance by 1 1/2 to 2 g's. [Ref. 23]

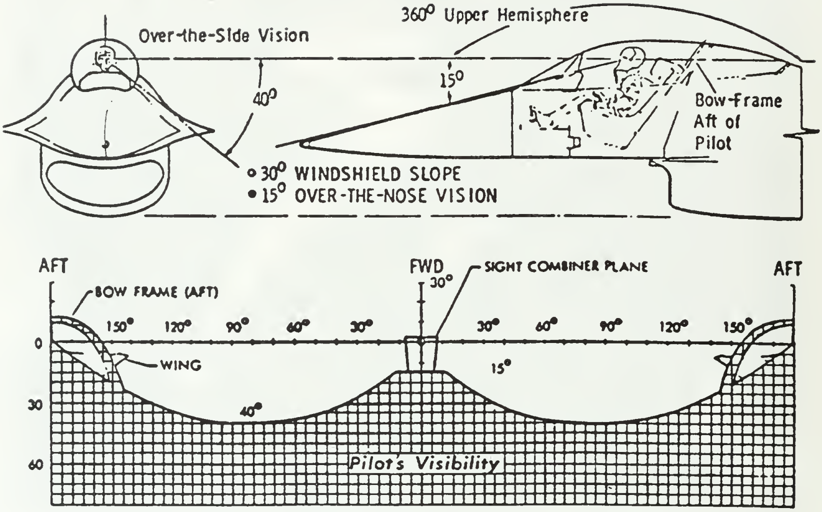


Figure 35. F-16 Cockpit Field of View. From Ref. [21].

The cockpit design is illustrated in Figure 36. Another striking difference from conventional practice was the control column. Rather than a center stick, the YF-16 had a sidestick controller on the right side of the cockpit with an armrest to support the pilot's arm during high g maneuvering. The sidestick was originally a fixed force controller with no displacement.

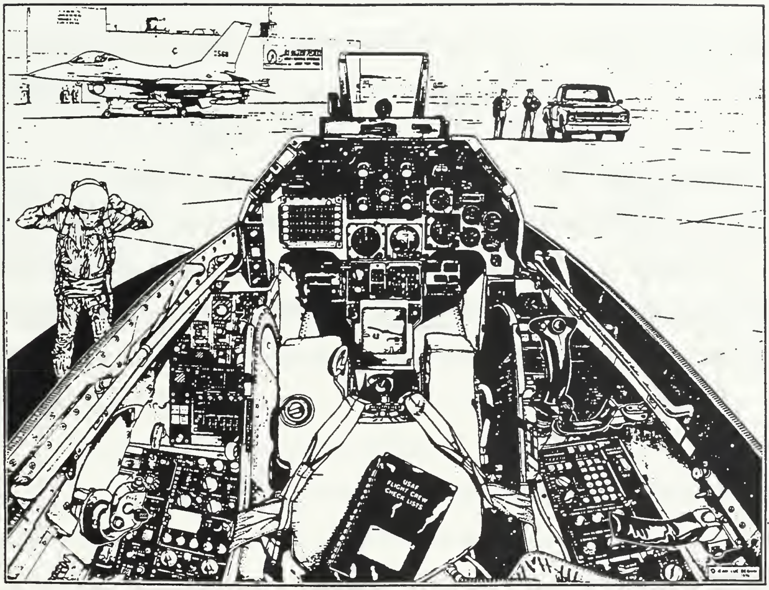


Figure 36. F-16 Cockpit Arrangement. From Ref. [21].

The reclining ejection seat position and raised rudder pedals eliminated some of the instrument panel space previously available. The instrument panel space was limited due to both the physical presence of the legs and flight boots and the need to provide clearance of the panel by the legs during an ejection. In order to minimize the need for instruments in the panel, the HUD was configured to be the primary flight display. The reduced panel size also caused adoption of a hands on throttle and stick (HOTAS) as had been demonstrated in the F-15. HOTAS was particularly useful due to the significant reach

distance to the instrument panel with the pilot's back in the backrest. Figure 37 illustrates the 50% smaller instrument panel available in the F-16 relative to the F-15 instrument panel. [Ref. 21]

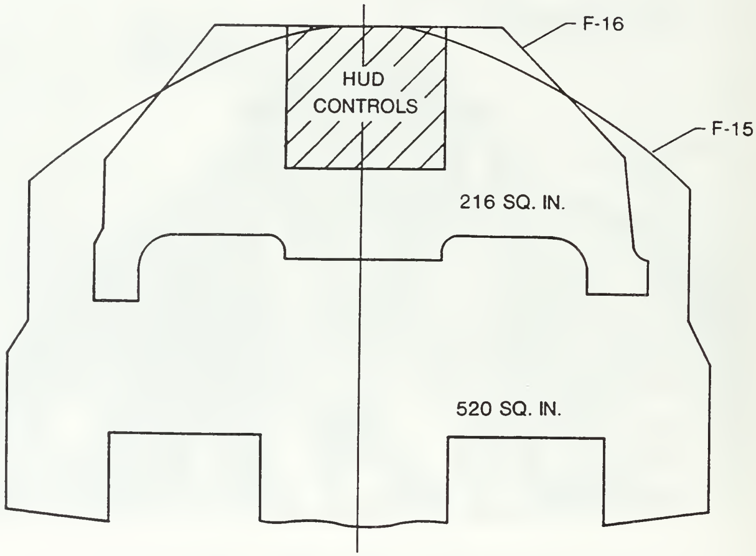


Figure 37. Instrument Panel Comparison. From Ref. [21].

b. Wing and Aerodynamics

The wing design was tailored to provide the pilot with a highly maneuverable airplane. The wing had only 4% thickness for high speed flight and acceleration. The smooth wing to fuselage blending reduced wave drag in the transonic and supersonic regime to permit rapidly closing the target, while increasing the wing stiffness and available internal fuel volume. The wing to fuselage blending also minimized

radar cross section which reduced detection likelihood. The long wing root extensions generated vortices which aided in maintaining attached flow over the wing at high angles of attack. The leading and trailing edge flaps were programmed by the flight control system in order to provide the pilot with the optimum wing camber for the current flight phase. Ventral strakes supplemented the vertical stabilizer for directional stability at the high angles of attack. [Ref. 17]

c. Armament

The 20mm M61A Vulcan cannon was located in the left wing root, with a 511 round ammunition drum behind the cockpit, which kept the mass close to the center of gravity and the moment of inertia low, enhancing the pitch acceleration. The cannon location was also selected to prevent the M61's heavy vibration from affecting the avionics or radar. Further, it avoided muzzle flashes in the pilot's face, as would occur with a nose mounting. [Ref. 17]

d. Flight Control System

A crucial technology for aircrew centered system design of the YF-16 was the fly by wire flight control system. It permitted the designers to incorporate relaxed static stability. The relaxed static stability is responsible for the F-16's rapid pitch acceleration by capitalizing on its inherent instability rather than trying to maneuver through positive static stability. Relaxed static stability also permitted use of a lifting horizontal tail which reduces trim drag. The relaxed static stability which yielded agility, also left the airplane inherently unstable and unflyable. With a lesser degree of instability, the pilot could make a pitch input to arrest a divergence from the trimmed condition. The YF-16 had such a large degree of instability (-10% static margin), that the time to double amplitude was considerably less than the reaction time of a fighter pilot to counteract. A sophisticated computer controlled stability augmentation system was designed to make control inputs to maintain the trimmed condition and prevent the airplane from departing controlled flight. The flight control computer system applied these control inputs independent of the pilot's

inputs. Other stability augmentation systems were of a limited authority design which could command only a small percentage of control surface deflection range, usually 10%. The reasoning was to provide the pilot with override capability should the stability augmentation system experience a runaway or hardover. The YF-16 stability augmentation system by comparison was a full authority design with 100% control surface deflection capability. The flight control computer could position a control surface anywhere within the range of motion to prevent the airplane from exceeding any limits programmed into the flight control computer, regardless of what the pilot might command. The YF-16 flight control computer was a quadruplex analog type. General Dynamics engineers believed that digital technology was too immature for such a critical application. [Ref. 18]

Fly by wire systems had flown as early as 1952 as a rudimentary single channel analog system tested aboard a Viscount airliner. The Panavia Tornado was the first production aircraft to have a fly by wire flight control system, however it retained a mechanical backup. The F-16 was the first production airplane to incorporate a fly by wire system flight control system with no mechanical backup. [Ref. 18]

The incorporation of a fly by wire flight control system in the YF-16 reduced the aircraft's weight through elimination of the conventional flight control system's hydraulic system with pumps, lines, actuators, and mechanical linkages. The elimination of a backup flight control system also was a weight savings. Any reduction in airframe weight can be translated into aircraft capability, particularly agility. Alternately, the weight savings accrued by eliminating the conventional and backup flight control system mechanical linkages can be used for weapons carriage or increased fuel, which yields more shots on target or increased time on station, both crucial to prevailing over the opponent. in a combat engagement Some of the weight savings were used in the inclusion of fail-safe and fail-operative design techniques into the flight control system architecture. [Ref. 18]

Through the use of the fly by wire flight control system, GD engineers were able to capitalize upon relaxed static stability and a lifting tail. The inherent instability allowed high maneuverability (control power i.e., rate commanded per unit size stick input) with modest control surface deflection for high g and supersonic flight. General Dynamics engineers estimated that the relaxed static stability and fly by wire reduced trim drag so greatly that a 400 pound reduction in aircraft gross weight resulted. [Ref. 18]

e. Overall Design Weight Savings

The use of relaxed static stability and wing/body blending resulted in a weight savings which GD engineers calculated as 1300 pounds compared to more conventional designs. This translated to a cost savings as well as performance enhancements. During full scale development (FSD), General Dynamics estimated the cost of an F-16 airframe at $60 per pound. The 1300 pound weight savings yielded a cost savings of $80,000 per airframe.

f. Prototype Competition

The YF-16 and the YF-17, as the Northrop airplane had become designated, demonstrated their relative strengths in the fly off competition. The two were fairly closely matched, and traded advantages in different regimes. The YF-17 had a better turn performance at Mach 0.7 and medium altitudes, but the YF-16 turn performance was superior as the airspeed increased. The two airplanes flew against each other in simulated combat. To even out skill and aircraft capability, the pilots would trade aircraft. In most cases, the YF-16 was the victor, but the reasons why were not clear. After considerable debrief and analysis, the difference was found to be not simply sustained g as both airplanes were designed for 9 g's, but rather transient performance. The YF-16 had superior agility through a faster roll rate and better acceleration, and thus could change state more quickly. [Ref. 17]

D. F-16 IN SERVICE

1. Full Scale Development and Production

The YF-16 won the fly off and then moved to become a production F-16A. However it was not to be the pure dogfighter any longer. The USAF and four European countries were the initial customers and demanded changes to the role of the aircraft. The Belgians in particular, and the other countries wanted a multi-role airplane for strike as well as air superiority. These requirements added approximately 2000 pounds to the airplane, stretched the fuselage by over a foot, the horizontal and vertical stabilizer areas were increased, and hard points were added. All of these reduced the thrust to weight ratio formerly enjoyed and reduced somewhat the agility. The F-16C took the aircraft weight to even greater extremes: while the YF-16 had a normal (air to air) takeoff weight of 21,000 pounds and a maximum takeoff weight of 27,000 pounds, the F-16C has a normal takeoff weight of 26,500 pounds and a maximum takeoff weight of 42,300 pounds. Thus the F-16C takes off at the YF-16's max weight, with an engine producing the same thrust. The YF-16's thrust to weight ratio was 1.13 and the wing loading was 70 pounds per square foot. The F-16C has a thrust to weight ratio of 0.9, a 20% loss and a wing loading of 88.3 pounds per square foot, a 26% increase. The changes decreased the airplane's sustained performance and agility. The internal fuel fraction has reduced as well from 0.29 to 0.24, reducing the ability to outlast the foe and requiring increased dependence on external tanks, hence weight and drag. [Ref. 17]

A fully combat capable two seat variant, the F-16B was developed for training purposes. The F-16B has also been used on highly demanding missions, most notably the Israeli attack on the nuclear reactors at Osirak. The inclusion of a second pilot position did penalize the internal fuel capacity by 17%, down by 1215 pounds to 5785 pounds. [Ref. 17]

The original simple radar was replaced by the Westinghouse APG-66 pulse Doppler unit, which added more air to air modes as well as air to ground navigation and mapping. This unit itself was later replaced by the Westinghouse APG-68 which offered refinements such as track while scan for up to 10 targets. [Ref. 17]

2. Engine Reliability Problems

The F-16 had reliability troubles with the early F100-PW-200, much like the F-15 which had the same engine. The problems were low cycle fatigue, fuel pump failures and stagnation stall. In the case of the single engined F-16, the problems could have greater consequences. Further, the F-16 engine had greater demands; as measured by engine cycles its F100 worked one third harder than the F-15 engine. The solution to the stagnation stall was the proximate splitter designed for the F-15, but never installed. The proximate splitter was an extension of the engine case aft of the compressor. It reduced the pressure surge from the afterburner by redirecting some primary airflow to the bypass air. This permitted more aggressive throttle manipulation by the pilot. Other engine modifications were adopted from the F-15 program and engine reliability improved markedly by 1981. [Ref. 18]

3. Combat Experience

The YF-16 has been a demonstration of aircrew centered design success. While the additional missions and weight growth of the F-16 have compromised the maneuverability of the airplane relative to the YF-16, it is still a very capable airplane. In one assessment: "The F-16 is popular with its pilots for its agility and sparkling performance. Alpha and g limiters... which prevent the aircraft [from] being inadvertently overstressed, giving carefree handling, leaving the pilot to concentrate on fighting the aircraft." [Ref. 17]

The 9 g design limit of the F-16 is probably the human limit to perform a military aviation task, given current technology [Ref.16]. The USAF has experimented with full body anti-g suits. These go further than the current abdomen and leg coverage anti-g suits

by incorporating anti-g bladders in a vest and even anti-g bladders in the helmet earcups and nape strap. Such technology could increase the g tolerance of the fighter pilot while greatly increasing the discomfort level.

The 9 g limit imposed by the flight control system is itself still controversial because it does restrict what the aircrew can do with the airplane. The perception is that g capability remains latent and unused, g capability which might be desired by the aircrew particularly in emergency or desperation. LT Randy Cunningham as pilot of a Navy F-4 with LT William Driscoll as RIO (radar intercept officer) pulled in excess of 12 g's to avoid being shot down while in combat. The Phantom, though mortally overstressed, survived and returned Cunningham and Driscoll to trap aboard the USS Constellation. The F-4 was written off as the maintenance effort required to repair the overstress damage was too extensive. The North Vietnamese thus achieved (unknown to them) an attrition kill, but the US Navy had a combat experienced pilot and RIO back to fight again. Cunningham and Driscoll went on to become the Navy's only aces of the Vietnam conflict. This was a case where the aircrew exceeded a limit and used up the airplane, but in doing so, survived the combat encounter.

The F-16 has demonstrated it's mettle in combat, primarily with the Israeli Air Force. Flying against the Syrian Air Force in the Beka Valley, which was armed with Russian aircraft, the Israeli F-16s posted a record of 44 victories with no losses. It was also the strike aircraft against the Iraqi nuclear reactors at Osirak. The Pakistani Air Force has also used the F-16 successfully in numerous victories over Afghan fighters in their border war. In USAF service, the F-16 has mainly seen service in the attack mission. It was however credited with an aerial victory in the Gulf War and did score the first kill with an AMRAAM while patrolling Iraqi no-fly zones. While not denigrating the skills of the Fighting Falcon pilots or the value of the airplane, it must be realized that the foes faced have not been front line, first world opponents. Unrealistic assessments of combat effectiveness must not be made from this data. [Ref. 17]

4. Criticisms of Cockpit Design Features

Some criticisms of the F-16 cockpit have emerged during it's service. Neck and shoulder strains are common due to craning around to check six while maneuvering at high g, and are attributed to the 30° reclining ejection seat. The sidestick controller has been identified by the Israelis as a potential combat liability. A pilot with an injured right arm has a chance of getting a center control stick equipped airplane home by flying with the left hand, while this is not possible with the sidestick. The sidestick also prevents use of the starboard console for any other significant purpose. As the sidestick was designed with a force transducer, an instructor in the F-16B cannot see the control inputs made by the student. Lastly, the absence of a canopy bow forward of the pilot precludes the installation of rear-view mirrors.

The next generation of fighters following the F-16 have not all embraced the cockpit design features of the Falcon, while relaxed static stability and fly by wire have seen wide acceptance. The Israeli Lavi, was designed with an upright pilot's seat and center control stick. The Eurofighter 2000 and Rafale have more conventional pilot's seats at 22° tilt, but retain the sidestick. The Swedish Gripen shares the selection of a 22° pilot's seat and has a center control stick. [Ref. 17]

E. FOCUS ON AIRCREW CENTERED DESIGN

The design of the F-16 used at least some degree of aircrew centered system design philosophy. The engineers actively sought out human factors research, transferring laboratory results and advanced technology into the airplane design. These translated into increased agility, capability and even reduced weight and cost. Some of the most notable of the design features were:

1. Superb field of view, which recognized the importance of visual search in air to air combat.
2. Fly by wire flight control system with relaxed static stability, which reduced the aircraft's weight, enhancing agility and performance while

even reducing program costs.

3. Increased pilot g tolerance through a reclined seat and raised heel line.
4. Incorporation of a HOTAS philosophy to keep the pilot's head out of the cockpit during the fight.

The F-16 has demonstrated in aerial combat around the world the value of the aircrew centered system design philosophy which shaped the airplane.

VI. CONCLUSIONS

A. AIRCRAFT SPECIFIC CONCLUSIONS

The review of aircrew centered systems design for the selected airplanes leads to a number of conclusions peculiar to that airplane. This section will examine those specific conclusions and draw general design guidelines.

1. Wright Flyer

The canard configuration was selected to provide to the pilot control of aircraft attitude throughout the entire flight regime. The pilot was prone in response to the drag reduction needed to sustain flight with the early low power output engines. The active participation of the pilot in controlling the Flyer was viewed by the designers as essential. The control system was designed to give the pilot control over pitch, roll, and yaw; and thus the flight path vector.

Compromise to a level of technology was necessary. When the technologies matured, and as flight test experience grew; aircrew centered system improvements were made. As engines became more powerful, upright seating was adopted. The upright seating was necessary for longer duration flights, passenger and demonstration flying, and flight instruction. The upright seating position also drove a major evolutionary change in the control mechanization. Independent control of all three axis was found to be necessary and incorporated. Aircraft rigging changes were adopted to improve lateral-directional flying qualities.

The Wright brothers succeeded because of their perseverance, innate engineering ability, and flying skills. They brought the focus of engineers and test pilots to the design process.

2. Spirit of St. Louis

Charles Lindbergh and Donald Hall point designed the Spirit of St. Louis for the Orteig prize mission. Lindbergh's primary requirement of pilot aft of all fuel cells drove the fuselage design. The airplane could not afford the drag penalty of a pilot position with

a canopy or windscreen to provide a forward field of view. Lindbergh and Hall consciously accepted the compromise to flying qualities, and utility in missions other than the Orteig prize, as being necessary.

The overall design requirements which shaped the Spirit of St. Louis were the result of a considered examination by Lindbergh of what was needed to achieve the goal. Today it would be termed operations analysis.

3. X-15

The X-15 design was successful due to an aircrew centered system design process. The pilot was vital for at least two reasons. First, the pilot was in place to conduct hypersonic research; to observe phenomena, to undergo real time aeromedical monitoring, and gain experience with control system applications for space and re-entry vehicles. Second, the pilot interacting with a control system permitted the flight control system to be much simpler and thus lighter as well. Simplicity was a key for reliability, and light weight was essential to preserve altitude and Mach number performance.

An aircrew centered operations analysis was conducted for the pilot escape system selection and design criteria. This analysis led to the supersonic ejection seat which saved 4000 pounds in aircraft weight compared to the other concepts, and prevented the loss of 800 miles per hour or a full Mach number.

As the aircraft control system matured, the value of a pilot was demonstrated by attaining and surpassing design specification goals. The range of controllable angle of attack was increased by 300%, altitude achieved bettered the specifications by 40%, maximum Mach number was 35% greater than the specification requirement.

Also demonstrated was the value of a pilot on board a research vehicle in the recovery of that vehicle from unforeseen emergencies. These included failures of the engine to start, engine failures during operation, "minor" explosions, and total electrical failures.

4. F-16

The design of the F-16 was a departure from the typical fighter aircraft design process which tended to be cutting edge technology driven. The F-16 began as a considered analysis of what a pilot needed in an airplane to be used for close-in combat. The results of this analysis were incorporated into a request for proposals. The YF-16 accomplished the requirements of the RFP with an aircrew centered system design approach.

The resulting YF-16 represented a return to the fighter pilot's airplane. It featured agility, a unique cockpit with a generous field of view, and suite of weapons and systems selected for the dogfight arena.

General Dynamics leveraged high technology in selected areas for payoffs in performance gains and weight reduction. The use of relaxed static stability, a computer controlled fly by wire flight control system, and wing/body blending saved 1300 pounds relative a conventional design. The YF-16's tranisent and sustained maneuver performance exceeded that of any competitors. A cost savings of $80,000 per airframe was realized through the weight savings.

While the F-16 in worldwide service may have been pressed into other roles and missions, with attendant weight and complexity gains, the airplane has retained much of its performance and maneuverability. It has also given a good record of itself, and it's pilots, in the crucible of combat.

B. GENERAL CONCLUSIONS

Each airplane analyzed represented a departure from conventional practice. The design process was started with a fresh approach to the mission and the role an aircrew member could play.

The aircrew brought to the aircraft the ability to adapt to changing missions and environments. The needs of the aircrew were accommodated to the extent and technology possible. Some basic lessons can be drawn from the airplanes reviewed. The aircrew

must be provided with flight control and mission systems consistent with the mission requirements. Displays must present the flight data and cues needed to fly the mission in a size, format, and at a location consistent with aircrew needs during dynamic flight evolutions. Integration of airborne systems must be such that operation can be readily learned and accomplished in the arena of flight, maneuvering and even combat.

A hallmark of each airplane analyzed was the in-depth involvement of aviators in the design process. From the requirements and concept definition phase, aircrew were part of the design team. For a successful aircrew centered systems design, aviators experienced in the intended mission must be involved in the design team. They must be knowledgeable as well of engineering and design, and further be able to articulate their expertise. These on-staff aviators should be on a full time status to the project and have some degree of authority over aircrew centered system design issues.

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